AL.3.1986-668

Monitoring the South Peak of Turtle Mountain 1980 to 1985

RMD Report 86/37

Alberta
ENVIRONMENT
Environmental Protection Services
Research Management Division

DDN
6707288

RESEARCH MANAGEMENT DIVISION EMBLEM

The emblem represents the interdisciplinary and holistic nature of the Division's environmental research programs. Each of the five sections of the symbol represent comprehensive programs on air, water, land, humans and their constant interaction. The sections converge to form a cohesive chain, characteristic of an effective research organization. This cohesive bonding makes the sections blossom into the environment in the form of a flower — an Albertan wild rose.

SEP 16 1986

MONITORING THE SOUTH PEAK OF TURTLE MOUNTAIN, 1980 TO 1985

RESEARCH MANAGEMENT DIVISION
Alberta Environment

Digitized by the Internet Archive
in 2016

https://archive.org/details/monitoringsouthp00crud

For further information about reports published by the Research Management Division, contact:

Research Management Division
Publications Office
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta
T5J 3N4

(403) 427-3946

This report may be cited as:

Cruden, D.M. 1986. Monitoring the south peak of Turtle Mountain, 1980 to 1985. Prep. for Alberta Environment, Research Management Division and Earth Sciences Division by Department of Civil Engineering, University of Alberta. RMD Report 86/37. 70 pp.

MONITORING THE SOUTH PEAK OF TURTLE MOUNTAIN, 1980 TO 1985

by

D.M. CRUDEN

Department of Civil Engineering
University of Alberta

for

EARTH SCIENCES DIVISION
RESEARCH MANAGEMENT DIVISION
Alberta Environment

RMD Report 86/37

1986

This report is made available as a public service. The Department of Environment neither approves nor disagrees with the conclusions expressed herein, which are the responsibility of the author.

TABLE OF CONTENTS

		Page
LIST OF TABLES		viii
LIST OF FIGURES		ix
ABSTRACT		xi
ACKNOWLEDGEMENTS		xii
1.	INTRODUCTION	1
2.	HISTORY OF DISPLACEMENT MONITORING AT TURTLE MOUNTAIN BEFORE 1980	2
2.1	Introduction	2
2.2	The Geological Survey of Canada, 1903 to 1931	6
2.3	The Research Council of Alberta and Others after 1931	7
2.4	Other Rockslides in the Alberta Rockies	14
3.	IMPROVEMENT OF THE MONITORING NETWORK	20
3.1	Introduction	20
3.2	Crack Motion Detection Gauges	20
3.3	Trilateral Signs	26
3.4	Other Displacement Records	44
4.	CONCLUSIONS	47
5.	RECOMMENDATIONS	49
6.	REFERENCES	50
7.	APPENDICES	53
7.1	Displacements Measured by the TM 71 Units	53
7.2	Data from Trilateral Signs	59
7.3	Documentation of Software for Trilateral Signs	62
7.3.1	Introduction	62
7.3.2	Theory	62
7.3.3	Preparation of Input Data	62
7.3.3.1	Station of the Trilateral Signs	62
7.3.3.2	Number of Measurements	63
7.3.3.3	Length of the Changeable Sides in Trilateral Arms	63
7.3.3.4	Angle between the Two Changeable Sides	63
7.3.3.5	Displacement Lines or Incremental Length of the Changeable Sides	63
7.3.3.6	Time of Measurement	63
7.3.4	Run Commands	64
7.3.5	Output from Run Commands	68
7.3.6	Worked Example	68

LIST OF TABLES

		Page
1.	Gapes in Feet of Cracks on Turtle Mountain	10
2.	Significant Displacements of Trilateral Signs	43
3.	Displacements Measured in the Vertical Plane by the Eastern TM 71 Unit	54
4.	Displacements Measured in the Horizontal Plane by the Eastern TM 71 Unit	55
5.	Displacements Measured in the Vertical Plane by the Western TM 71 Unit	56
6.	Displacements Measured in the Horizontal Plane by the Western TM 71 Unit	57
7.	Data from Trilateral Signs, 1980	60
8.	Data from Trilateral Signs, 1981 to 1984	61

LIST OF FIGURES

		Page
1.	Localities around the Frank Slide	3
2.	Oblique Aerial View of the Frank Slide from the Northeast	4
3.	Cross-Section through Turtle Mountain	5
4.	Map of Fissures on the Crest of Turtle Mountain	9
5.	Photographs of the East Face of Turtle Mountain Emphasizing Its Skyline	12
6.	Expected and Observed Frequencies of Major Slope Movements in the Alberta Rockies as Shown on NTS Sheets	16
7.	Distribution of Major Slope Movements in the Alberta Rockies	17
8.	Distribution of the Minimum Dimension of Slope Movements in the Alberta Rockies	18
9.	Location of TM 71 Crack Monitors	22
10.	Displacements Measured by the Eastern TM 71 Unit	23
11.	Displacements Measured by the Western TM 71 Unit	24
12.	Map of the Trilateral Signs	28
13.	A Trilateral Sign	30
14.	Analysis of Trilateral Sign Data	31
15.	Displacements in Sign A	33
16.	Displacements in Sign B	34
17.	Displacements in Sign C	35
18.	Displacements in Sign D	36
19.	Displacements in Sign E	37
20.	Displacements in Sign F	38

Continued ...

LIST OF FIGURES (CONCLUDED)

Page

21. Displacements in Sign G 39

22. Displacements in Sign H 40

23. Displacements in Sign I 41

24. Results of Hourly Monitoring by Tape Extensometer 42

ABSTRACT

This report describes the improvement of a monitoring network installed by J. Allan in 1933 for the Alberta Department of Public Works on Turtle Mountain in the Crowsnest Pass district of southwestern Alberta.

The network was extended in the summer of 1980 to all accessible sites at the margins of a 5×10^6 m^3 rock wedge that may fall eastward from the South Peak of Turtle Mountain. A network of eyebolts anchored in rock some distance from the gaping cracks is at least an order of magnitude more sensitive to movements than the previous network. Two TM 71 crack monitoring instruments can detect movements of 0.1 mm.

Significant eastward horizontal movements of the order of 1 mm/a have been detected by the TM 71 instruments. No significant movements have been detected by tape extensometer measurements between the eyebolts. No hazardous movements have been detected and the measurements give no cause for immediate alarm. Rates of movement over 12 mm/d should be considered hazardous.

It is recommended that annual monitoring of the network continue until the causes of the observed movements are better understood.

ACKNOWLEDGEMENTS

The Scientific Authority for this project, D.W. Prosser, gave valuable advice on technical matters and was a cheerful and hardworking participant in our fieldwork. The success of the project owes much to him and to other members of the field parties: R. Baldwin, P. Barlow, Dr. C. Beaty, M. Boon, Dr. D. Bingham, Dr. H. Charlesworth, Z. Chen, K. Chiste, Dr. S. Evans, Dr. D. Fabre, K. Fossey, L. Fuming, D. Fushtey, S. Gamble, D. Gillard, B. Gudmunsdottir, C. Holt, Dr. O. Hungr, K. Ishikawa, C. Jardine, B. Larsen, Dr. J. Locat, Z.Y. Lu, Dr. D. McCreath, P. McLellan, W. Milne-Holme, H. Regier, and D.T. Sneddon.

B. Kostak of the Institute of Geology and Geotechnics of the Czechoslovak Academy of Sciences has provided considerable careful guidance in the interpretation of the TM 71 observations.

C. Jardine and D.T. Sneddon of the Research Management Division, Alberta Environment, have been constant spurs in the definition and pursuit of issues raised by the measurements reported here. The Research Management Division and the Earth Sciences Division of Alberta Environment have provided major funding for this work. It was also supported by the Natural Sciences and Engineering Research Council Grant A8533 to D.M. Cruden.

1. INTRODUCTION

This report summarizes work by personnel from the departments of Civil Engineering and Geology at the University of Alberta during a series of annual contracts with Alberta Environment beginning in April 1980 and extending to April 1985. It is intended to bring together information necessary for understanding the current program of monitoring surface displacements around the South Peak of Turtle Mountain.

Section 2 is a brief history of monitoring programs and other relevant activities from the date of the Frank Slide in April 1903 until the beginning of the involvement of Alberta Environment personnel in 1980. Section 3 of the report reviews observations from the displacement monitors up to the end of the 1984 observation season. Most of the data used to support the conclusions are tabulated in appendices.

The east side of Turtle Mountain, south from South Peak to Drum Creek, has been mapped geologically at a scale of 1:5000 or in more detail. Preliminary results for the vicinity of the South Peak are given in Cruden (1983b). A companion report will provide a fuller summary (Fossey 1985).

2. HISTORY OF DISPLACEMENT MONITORING AT TURTLE MOUNTAIN BEFORE 1980

2.1 INTRODUCTION

The Frank Slide occurred at ten minutes after four in the morning of 1903 April 29. Frank, a coal mining town in the Front Ranges of the Canadian Rockies in the Crowsnest Pass in southwestern Alberta, was about 2 km south of the present settlement of that name, which is now part of the Municipality of Crowsnest Pass (**Figure 1**). The slide moved down the east face of Turtle Mountain. It crossed the entrance of the Frank Mine of the Canadian-American Coal and Coke Company, the Crowsnest River, the southern end of the town of Frank, the main road from the east, and the Canadian Pacific main line through the Crowsnest Pass. Raised ground to the east absorbed the momentum of the debris, but huge boulders of limestone covered the spur railway line to Lille, then under construction (**Figure 2**).

In 100 seconds, nearly 3 km^2 had been submerged under an average of 14 m of rubble. Thirty million cubic metres of rock had moved. Seventy people were buried. These people were not buried by dust, but by rock. Rock dust, thrown up from the debris, caused violent electrical discharges during the slide, and settled like a pall over the valley.

The Department of the Interior sent two of the Geological Survey of Canada's most experienced "mountain men," R.G. McConnell and R.W. Brock, to investigate. Their report, completed within a month of the disaster, attributed the "primary cause" of the slide to "the structure of the mountain" (McConnell and Brock 1904:17).

Interpretation of the bedrock structure has changed since the report, but the conclusion has not. To see this, imagine looking at a vertical cut across the north-south trending ridge that forms Turtle Mountain. **Figure 3**, a deep east-west section, shows that the beds of limestone that form the ridge had been bent into a great arch, the Turtle Mountain Anticline. During the formation of the Rockies tens of millions of years earlier, this limestone was thrust eastward along the Turtle Mountain Thrust Fault over upturned and younger coal-bearing rocks. During the slide, the east limb of the arch slid out along a thrust fault and over the coal mines (Cruden and Krahn 1973).

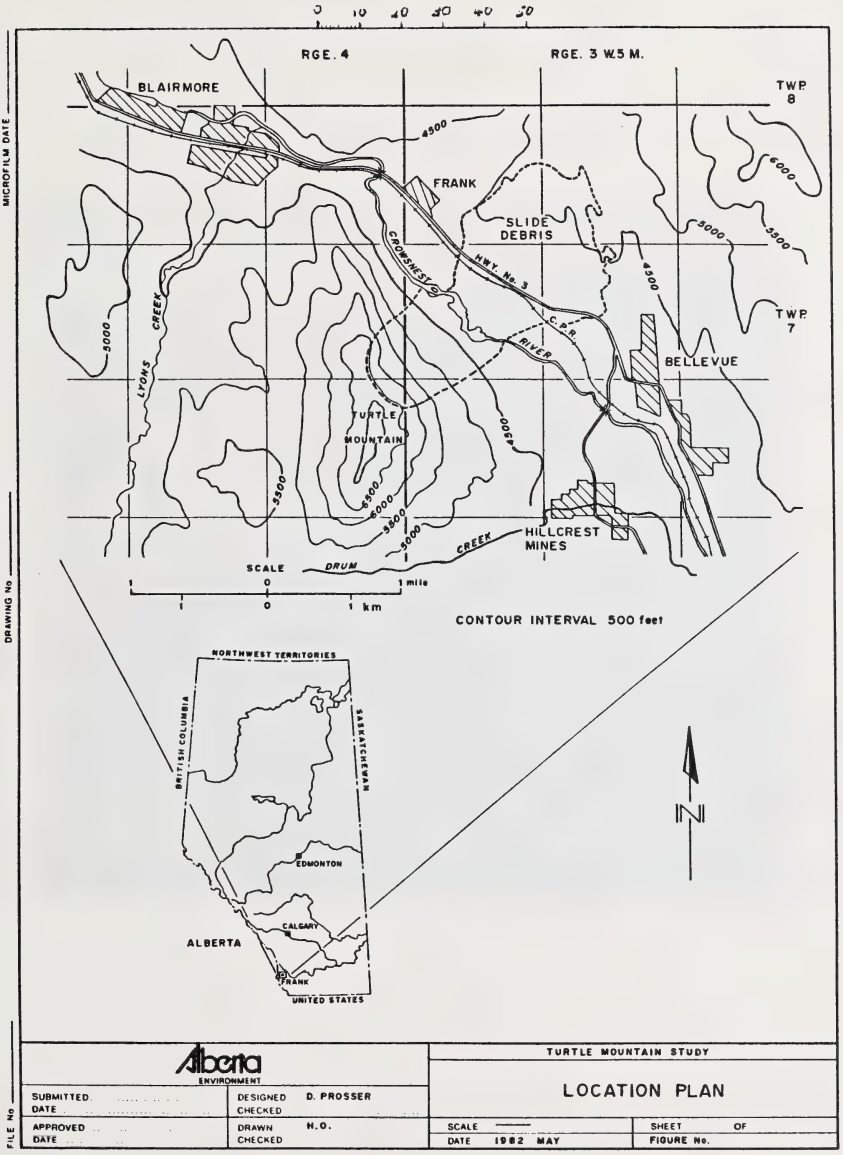


Figure 1. Localities around the Frank Slide.

Figure 2. Oblique aerial view of the Frank Slide from the northeast (photograph by C. Beaty).

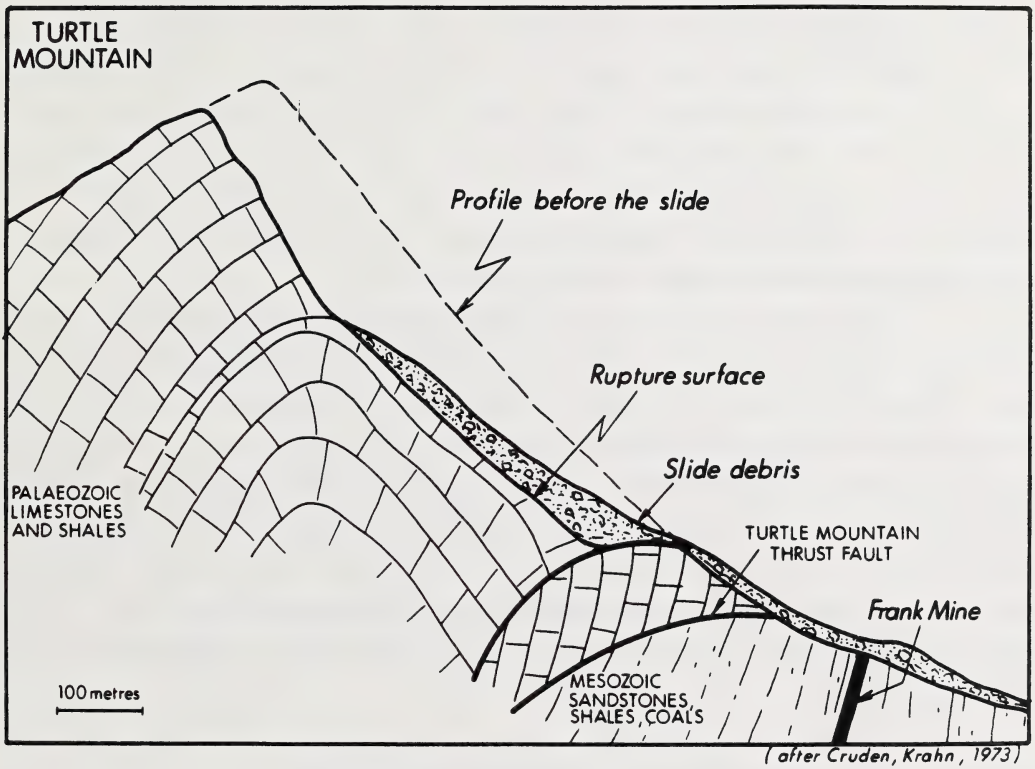


Figure 3. Cross-section through Turtle Mountain.

Figure 3 also shows the seams of coal that were being mined at Frank. Notice that none of the coal rocks were involved in the slide. Indeed, all the miners underground at the time of the slide survived, and there was comparatively little damage to the underground workings (Dowlen 1903). However, the mines inspector commented in a later (private) letter: "There was never any doubt in my mind as to the cause [of the slide] . . . It came from robbing that coal seam that was being operated" (Kerr 1979:60).

In a letter to the Alberta Deputy Minister of Public Works, Brock (1910a) stated that the Frank Slide "was caused by the mining of coal. . . . There is no doubt in my mind." Intuition and circumstantial evidence led to the conclusion that the Frank Slide was the first example in the Rockies of environmental mismanagement by the energy industry.

The history of subsequent investigations of Turtle Mountain can be divided into phases that saw the involvement of various agencies. Early work was led by the Geological Survey of Canada. The Research Council of Alberta became involved in 1931. Research in rock slope stability received an impetus from the federal government's sponsorship of the Pit Slope Program from 1972 to 1977, which drew the University of Alberta's Civil Engineering Department to re-examine the slide and bring it to the attention of Alberta Environment. In this chapter, each of these phases is briefly reviewed and, in a final section, the Frank Slide is placed in the context of slope movements in the Alberta Rockies.

2.2 THE GEOLOGICAL SURVEY OF CANADA, 1903 TO 1931

Brock became director of the Geological Survey of Canada, but he did not lose sight of Turtle Mountain. He visited the site in 1909 (Brock 1910b) and 1910 (Brock 1911), and worried about another slide from the North Peak of Turtle Mountain. "A large slide would cut off all railway communications and close the mines west of Frank. It might permanently close the Pass. The town of Frank would be wiped out with a fearful loss of life," he wrote to the Alberta Deputy Minister of Public Works on 1910 November 03.

As a result of his concerns, he vigorously opposed the southerly expansion of a shaft mine that had been opened in the same seam to the north of the debris.

A complex series of events led a Royal Commission to arbitrate between the coal company and the federal and provincial governments. Its report (Daly, Miller, and Rice 1912) confirmed Brock's view that continued mining immediately north of the slide debris threatened the town. As a result, the provincial government supported the relocation of the town of Frank to a new site owned by the mining company. Further progress of the shaft mine southward was halted by fear of water inflows. The Royal Commission's report also emphasized the need to leave sufficient coal in the drift mine to support the South Peak of Turtle Mountain.

Before the slide, about a quarter of a million tonnes of coal had been taken. Over twice as much extraction occurred after the slide, between 1903 and the end of 1910, as mining progressed beyond the south edge of the slide. The resulting subsidence broke through to the surface, and the path of the old workings under the east slopes of Turtle Mountain can still be seen. The drift mine removed a further 500 000 t of coal in the six years following the Commission's report. The mine was closed after a fire that had been burning in the mine since 1910 broke through into the recent workings. The extraction rate from the seams is estimated to be 50%.

2.3 THE RESEARCH COUNCIL OF ALBERTA AND OTHERS AFTER 1931

By 1930 the workings of Hillcrest Colliery had edged northward from the village of Hillcrest onto Turtle Mountain, and residents had become concerned for their safety. As a result, B.R. McKay, who had been in the topographic mapping party assisting the Royal Commission, was asked by the Geological Survey to once again examine Turtle Mountain when he returned to the Crowsnest Pass in 1931 in the course of his duties as a coal geologist. He noticed changes in the South Peak area, which he viewed to be "the most unstable portion of the Mountain at the present time. . . . [It was] almost completely surrounded by fissures" (McKay 1931). The Alberta Government sent John Allan, a Professor of Geology, Consulting Engineer, and a founding member of the Alberta Research Council, to investigate. He recommended relocation of those living close to the south margin of the slide and removal of the road through the pass to the east of the CPR line (Allan 1933). The provincial government offered residents of the zone identified by Allan as being

threatened by movements from the South Peak of Turtle Mountain half the cost of moving their homes to new sites farther east. The highway was relocated to the alignment of Highway 3 shown in Figure 1. Coal mining on the slopes of Turtle Mountain was stopped. The slide is now a Provincial Historic Site and a Restricted Development Zone.

Dowlen (1903:12) had placed "twelve reference mounds at points where movement can readily be detected." During a three weeks' stay in Frank, "there was no shifting whatever." The members of the Royal Commission (Daly, Miller, and Rice 1912:21) were "unsuccessful in their search" for the "plot or instrumental record" of the 1903 survey. They commented that "for future guidance, it is desirable that monuments be established in the vicinity of the crevices, so that any movement may be accurately measured."

During June and July of 1933, Allan, under instruction from the Alberta Ministry of Public Works, carried out a survey of the cracks in the crown of the Frank Slide on Turtle Mountain. Allan (1933) identified Fissure 1 as "the major break of first rank significance," and commented, "No. 1 fissure almost encircles South Peak on the west side, and outlines a block extending from a point 300 feet south of South Peak to a point about 600 feet N 10^{o} W of South Peak. . . . At 7,000 feet, 300 feet southeast of South Peak there is a perpendicular cliff in which the rock is badly cracked. This represents the bottom of the unstable part of South Peak . . . a pyramid block of over 7,000,000 cubic yards." He established 18 monitoring stations (Figure 4), paint marks on either side of gaping cracks, and recommended (Allan 1933) that these stations be resurveyed at intervals.

The results of further surveys carried out by Allan, Alberta Environment, and by members of the Department of Civil Engineering, University of Alberta, form Table 1. The original measurement units, feet, have been retained. These and other less complete surveys have been discussed by Cruden, Prosser, and Sneddon (1982), who suggested that 0.04 ft. (12 mm) represents a significant change in gape.

Stations 15 to 18 at the northern end of the slide crown showed opening in the five years between Allan's surveys. Byrne in the 1950s was unable to find any of Allan's stations at the North Peak, but Cruden located Station 16 in 1977. Measurement showed continued dilation. Each of these

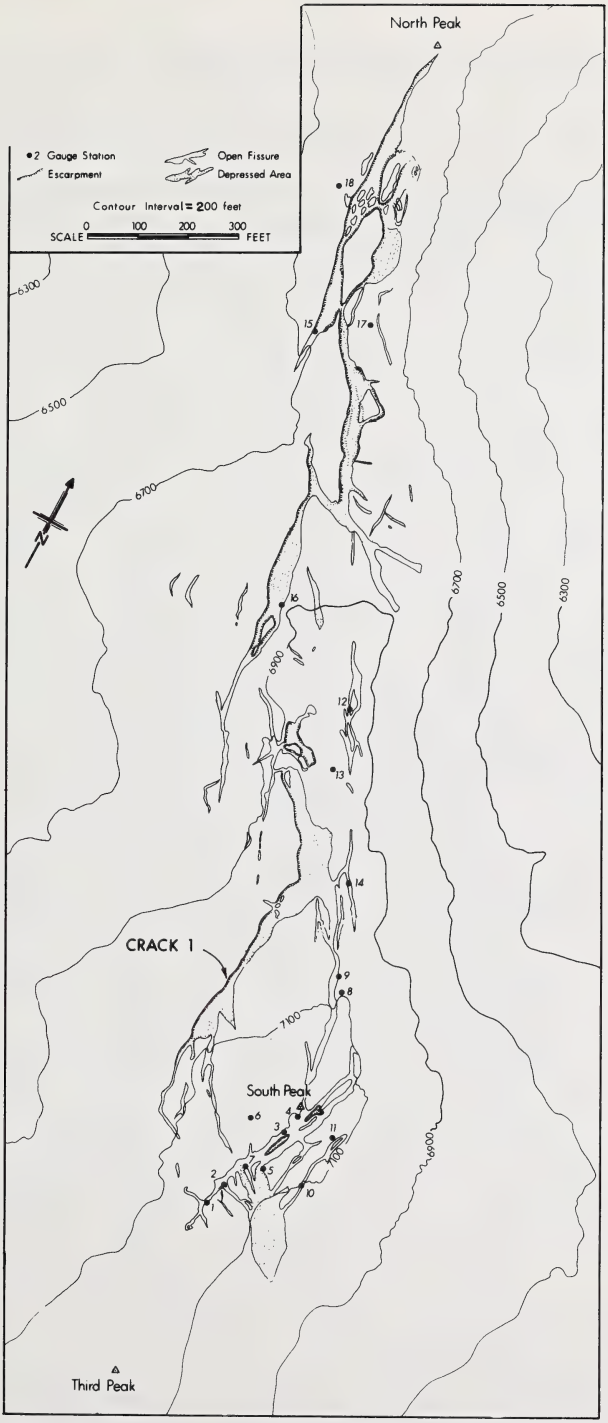


Figure 4. Map of fissures on the crest of Turtle Mountain.

Table 1. Gapes in feet of cracks on Turtle Mountain. (All values given in feet.)

Station	Date					
	33/07/?[a]	34/07-08/?[a]	38/09/04	80/07/30	83/06/13	84/06/26,28
1	0.63	0.78	0.66	f[b]		
2	1.65	1.82	1.69	1.64	1.65	1.63
3	4.10	4.10	4.15	4.16	4.16	4.17
4	3.35	3.40	3.39	3.34	3.33	3.33
5	4.10	4.17	4.23	4.19	4.19	4.19
6	0.54	0.65	0.54	0.52	0.51	0.52
7	8.70	8.90	8.86	8.79	8.80	8.78
8	f[b]					
9	0.65	1.02	f[b]			
10	0.87	1.04	1.04	f?[c]		
11	2.70	2.90	2.80	2.73	2.69	2.71
12	3.50	3.80	3.71	3.62	3.60	3.65
13	3.30	3.40	3.39	3.32	3.30	3.31
14	3.70	3.65	3.63	f?[c]		
15	4.08	ND	4.15	f[b]		
16	14.37	14.30	14.52	f[b]		
17	1.67	ND	1.71	1.63	1.63	1.63
18	0.98	ND	1.01	f[b]		

[a]/? = day unknown
[b]f = rock fall (known occurrence)
[c]f? = presumed occurrence
ND = no data

stations is located on a crack running parallel to the slide scarp. Cracks in this orientation might be expected to open if the rock between the crack and the scarp moves outward. The thorough search conducted in 1980 revealed fallen rock at Stations 15, 16, and 18, confirming that local extension had taken place. Station 17 appears to be stable.

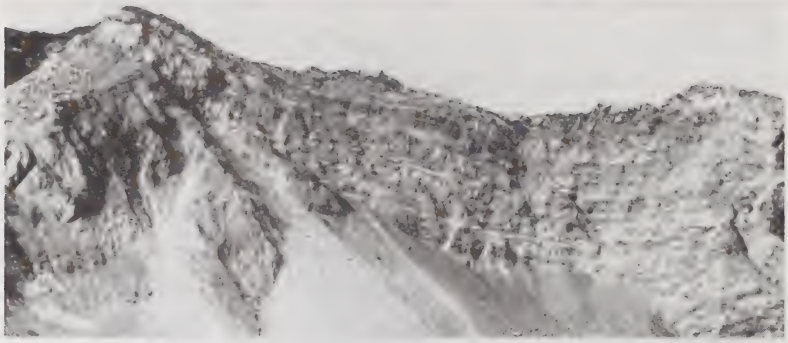
There is an eyewitness account of a rock fall from the mountain crest close to these stations on 1954 May 25. A pillar of rock, locally called the Turtle Man, toppled during a thunderstorm (Kerr 1979:64). The pillar can be clearly seen on the skyline of a Geological Survey of Canada photograph of the old road through the slide (Figure 5b) taken in 1942 (GSC photo 92136 by G.S. Hume). A photograph (Figure 5c) taken in 1977 with a Wild P32 photogrammetric camera documents the change in the skyline since 1942. Comparison with an earlier photograph (Figure 5a) from 1911 (GSC photo 20264 by W.H. Boyd) shows that Turtle Man is the remnant of some earlier falls between 1911 and 1942.

Three other stations were located for the first time since 1938 in the Department of Environment's 1980 search. Stations 11, 12, and 13 were observed to gape at close to their 1933 values. Station 10 had shown a 20% increase in gape between 1933 and 1938, and Station 14 was the only station to show a decrease in gape in that time period. Such anomalous behaviour indicates instability. Now only half of Station 10 remains; Station 14 could not be located, and has presumably fallen.

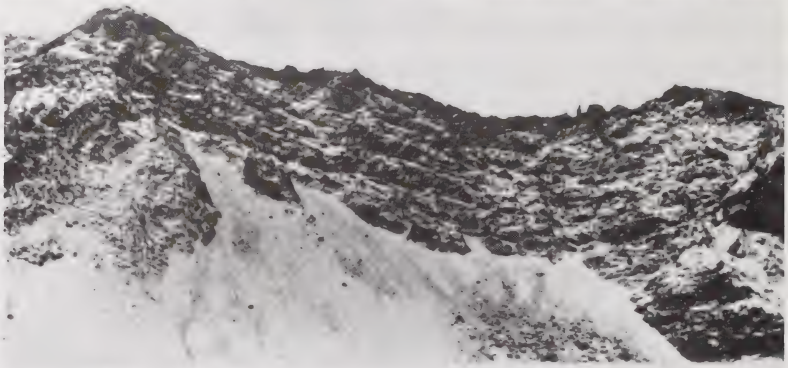
Stations 1 to 7 are on cracks running almost perpendicular to the ridge crest. Part of Station 1 has been dislodged; the other stations show no simple pattern of movement, possibly because significant outward movements would appear as shears along the cracks rather than dilations of the cracks. For a crack, open 4 ft. (1.2 m), a shear displacement of 1 ft. (300 mm) is necessary to show a significant increase of 12 mm between points on either side of the crack. At Stations 3 and 5 for instance, up to 2.5 ft. (0.76 m) of shear movement may have taken place since 1933.

Since 1971, measurements at the stations have been conveniently made with an extending steel tape. Standard deviations of repeated measurements at a station are of the order of 0.01 ft. (3 mm); the largest source of scatter probably arises from difficulties in exactly replicating each measurement.

5a



5b



5c

Figure 5. Photographs of the east face of Turtle Mountain emphasizing its skyline (photograph 5a by W.H. Boyd 1911; photograph 5b by G.S. Hume 1942; photograph 5c by D.M. Cruden 1977).

Allan's paint marks have diameters of 30 mm and are no longer easily distinguishable. In addition, temperature corrections of the tape or the use of a higher quality surveying tape are unlikely to produce more precise measurements if measurement end points are indistinct.

Slope movements may also be obscured by cyclic changes in crack width caused by changes in moisture and temperature of the rock mass between cracks. As the temperature rises in the spring, ice formed in cracks within the mass may thaw, causing deflation of the mass. The moisture released in melting may contribute to pore pressures within the mass, dilating it. This moisture may also be absorbed by the rock with some dilation (Hudec and Sitar 1975). A rise in temperature of the mass will cause some expansion, which could be noticeable if the masses between the cracks are large. Expansion due to heating would show both as a diurnal change and as a seasonal cycle. During summers, warming penetrates more deeply into the rock mass. Similar short- and long-term cycles are exhibited as water content changes after precipitation.

Changes are difficult to assess. Differences observed between the apparently stable stations on the south side of the slide may only be a matter of millimetres. Clearly, if precise measurements are to be made, these cyclic changes should be understood and taken into consideration. Comparison of the two most complete sets of data since 1933, those of 1938 and 1980, shows eight significant changes, all decreases in gape since 1938. This pattern of behaviour probably occurs because the 1938 observations were taken in September, when gapes would have increased as the rock contracted with the seasonal decline in average temperature. Differences between the 1933 and 1980 observations, both taken in mid-summer, are less pronounced. Four of the 1980 observations indicate an increase in gape, and one shows a significant decrease in gape.

A review of the data from Allan's stations shows:

1. Only 10 of the 18 original stations remain operative. Six stations have been destroyed by rock fall, and this is likely the fate of the two others, which could not be found in recent times.
2. None of the operative stations are sited to detect the extensional movements that might precede failure along Allan's Crack 1.

3. Crack widths may have fluctuated by as much as tens of millimetres over the June-September measurement season. These movements may mask shear movements along existing cracks.

2.4 OTHER ROCKSLIDES IN THE ALBERTA ROCKIES

One of the reasons Brock was convinced that coal mining was responsible for the Frank Slide is indicated in his 1904 report (McConnell and Brock 1904:17): "In the Alps, destructive landslides have been quite frequent, but are exceedingly uncommon in the Canadian Rockies. None at all approaching this one in size has ever been recorded."

More recent work has modified this view. Gardner (1980) has suggested a frequency of one major movement every 5000 years in a 100 km^2 area at or above the treeline in the southern Canadian Rockies. A similar figure has been derived from a survey of the central Southern Alps in New Zealand by Whitehouse and Griffiths (1983).

The assumptions underlying these estimates can be made explicit by examining the results of the reconnaissances of surficial deposits in the Rockies in Alberta undertaken by Bayrock and Reimchem (1976a, b, c; 1980). Nine hundred and thirty-five large rockslides were located in about 60 000 km^2, to give a density of 1.57 rockslides per 100 km^2. Some rock glaciers, large rockfalls, and debris slides may be included in that total; on the other hand some rockslides, such as those at Jonas Creek (Bruce and Cruden 1980), were not recognized in the survey and contiguous slides were counted as single events, so the total is probably a reasonable estimate of the number of visible slides.

Cruden (1982a) has suggested that it takes in the order of thousands of years for a major rockslide to become sufficiently overgrown by the natural vegetation in the Rockies to be obscured in a reconnaissance survey. The rate of growth depends on the climate and the nature of the slide debris. Debris from mudstones, shales, slates, schists, and other materials that weather quickly to clay minerals promotes rapid recovery of the natural vegetation; slide debris with large blocks of limestone or sandstone is more persistent. Above the treeline, only erosion or deposition by colluvial or alluvial glacial processes obscures the evidence of earlier slope movements.

Close to and above the treeline the number of visible slides represents a good approximation of the accumulation of events since the last retreat of the glaciers about 10 000 years ago; in more moderate climates the record is probably an order of magnitude shorter. We can expect then to be within the correct order of magnitude if we consider the visible slides as the accumulation of about 5000 years of activity.

If the slides were randomly distributed throughout the Alberta Rockies, about six slides might be expected in each of 152 National Topographic System (NTS) 15-minute quadrangles (and parts of quadrangles). The scatter of observed frequencies should be described by a Poisson distribution. **Figure 6** shows that the fit to a Poisson distribution can be rejected. **Figure 7** indicates a concentration of slide activity in a band east of the Pacific watershed and parallel to it. With most landslides, about 5% of the NTS sheet is occupied by landslide debris. Thus on the scale of Radbruch-Hall et al. (1982), the landslide incidence is moderate, and similar to estimates immediately to the south in the United States.

The distribution of the minimum dimension of the areas covered by slide debris is shown in **Figure 8**. As might be expected, the frequency of the slides decreases rapidly with their size. The distribution is truncated at 100 m by the nature of the survey; units smaller than this were not mapped. Some informal censoring of the distribution may also have taken place where units were above this limit in areas of complex geology. The overall form of the distribution, approaching negative exponential, suggests the minimum dimension of a movement may be controlled by a Poisson process. Such a model would be compatible with observed distributions of both the length of natural fractures and the spacings between them. Its further development would contribute to a better understanding of the risk of slope movements in the Rockies.

It seems reasonable, then, to conclude that some natural processes particularly prevalent in a belt east of the Pacific watershed are contributing to slope instability there. Turtle Mountain lies within this belt, and some natural processes that contributed to the slide (the destruction of cohesion along bedding planes by limestone solution and by freeze-and-thaw weathering) have probably been accelerated by the movement-

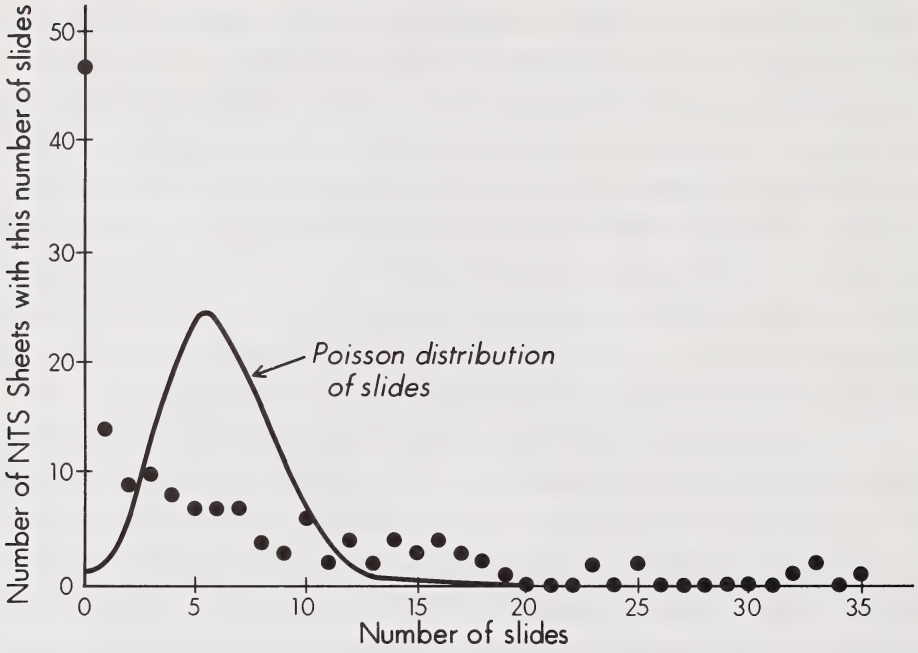


Figure 6. Expected and observed frequencies of major slope movements in the Alberta Rockies as shown on NTS sheets. The horizontal axis gives the number on each NTS sheet; the vertical axis give the frequency of that number. The solid line shows frequencies predicted by a Poisson distribution.

Figure 7. Distribution of major (>100 m) slope movements in the Alberta Rockies.

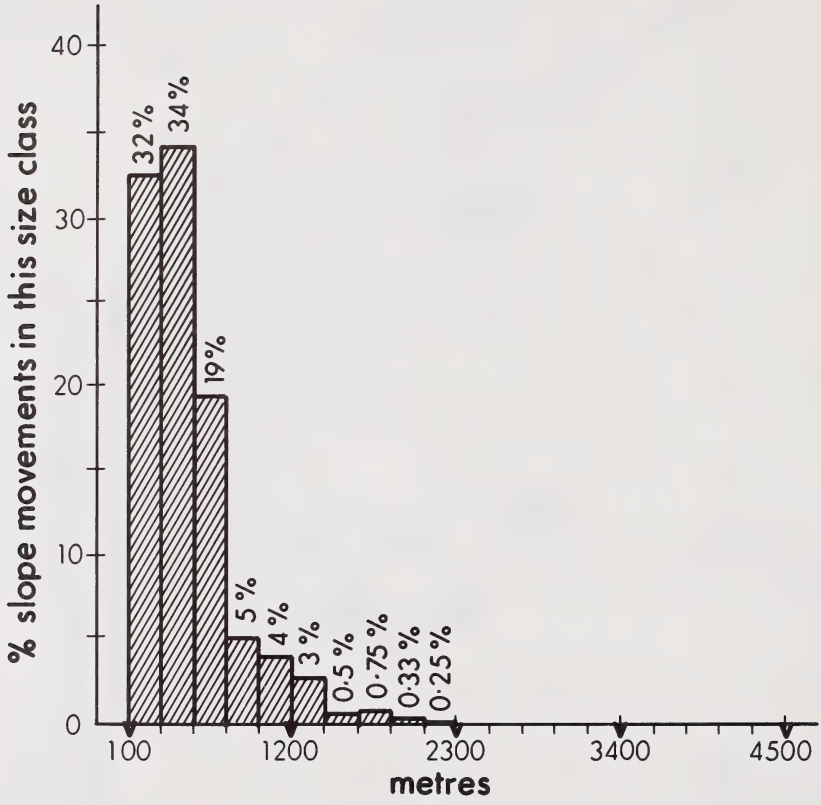


Figure 8. Distribution of the minimum dimension of slope movements in the Alberta Rockies.

induced fracturing of the rock mass in the crown of the slide. Other processes such as the removal of lateral support for the rock mass by slush avalanches down the steeply inclined gullies on the east face of the mountain are probably less important, since the slide reduced the mass requiring support.

A major source of anxiety not present elsewhere in the rock slide belt of the Rockies is the fire burning in the coal mine since 1910. It may have been extinguished (Allan 1933), but its continued activity could trigger the destruction of the coal pillars maintaining the mine openings. The resulting closure, with horizontal movements in the order of a metre, could be transferred up-slope and result in some loosening of the rock mass around South Peak, with the possibility of initiating further major slope movements.

3. IMPROVEMENT OF THE MONITORING NETWORK

3.1 INTRODUCTION

Larocque (1977) recognized three levels of activity in a typical open pit mine monitoring project. At Level I, monitoring is designed to locate areas of potential instability. Level II involves the detailed observation of potential instabilities recognized in Level I. Level III monitors actual instabilities so that activities in the area of the instability may be safe.

When Allan (1933) identified an area of potential instability at the South Peak of Turtle Mountain, this project moved to the start of Level II activities. Larocque (1977) commented, "Level II. When a potential instability is detected, the monitoring effort must be intensified. It is important to determine:

a. the area and boundaries of the unstable zone,
b. the amount and rate of movement,
c. the general direction of motion."

Allan (1933) provided an hypothesis about the boundaries of the unstable zone and left the amount and rate of movement to be determined along with the general direction of motion. In the network that Allan set up, only Station 2 is sited to detect movement of the wedge. Thus, the establishment of other stations around the wedge was a priority.

3.2 CRACK MOTION DETECTION GAUGES

Two TM 71 crack motion detection gauges were available on loan from the Institute of Geology and Geotechnics, Czechoslovak Academy of Sciences. These instruments show motion by changes in the Moire fringe interference patterns produced by superposed grids fixed to opposite sides of a crack (Kostak 1969). Movements as small as 0.1 mm may be detected when temperature fluctuations at the site are small (Kostak and Rybar 1978). Two sets of grids mounted orthogonally give the three-dimensional movement vector and a check for consistency.

Because this was a trial installation designed in part to test the performance of the TM 71 devices under the severe weather conditions on the mountaintop, both instruments were installed in Fissure 1 immediately east of

Station 2 and within 2 m of one another (**Figure 9**). The site was chosen for its accessibility because the crack was sufficiently wide to accommodate the devices and because the accumulation of talus in the crack provided a working floor.

The grids are supported by holders, thick-walled hollow steel tubes grouted into holes drilled up to 400 mm deep into the crack walls. An AX diamond drill bit driven by a chainsaw motor was used to drill the limestone. The remoteness of the site (which required the backpacking of all equipment to it), inclement weather, and inexperience with the drill all contributed to delays. It is expected, however, that under more favourable conditions the TM 71 can be installed in less than a day and be ready for reading when the grout has set. More details of the installation procedure are given by Cruden (1982b).

The instruments were installed in June 1980; observations of them are recorded in Tables 3 to 6 in Appendix 7.1. Clearly the instruments survived the severe winter conditions on Turtle Mountain. No damage was apparent, apart from some rusting of the containers and the locks. The locks were replaced in June 1982. Routine maintenance was confined to removing dust from the glass plates of the instruments with a camera lens brush.

The displacements have been summarized in **Figures 10 and 11**. To compile these graphs from Tables 3 to 6, observations were adjusted to zero, and the displacements of the grids at their time of installation and the redundant observations in the x direction from both the horizontal and the vertical grids were averaged.

The largest movements are evident in the y direction, parallel to the edges of the crack. This is the direction that gauging stations set up by Allan (1933) are ineffective in detecting movements. Reference to Figure 9 shows that the sense of the movement recorded on the east and west gauges coincide. Assuming the south side of the crack has remained stationary, the north side has moved about 1 mm eastward toward the Crowsnest River Valley over the winter of 1980-1981. No significant movement was shown in the y direction in 1982. Movement resumed in 1983 to give a total displacement at the end of the summer of 1983 of about 2 mm over the three years of observation of the west gauge. Smaller movements were recorded by the east gauge.

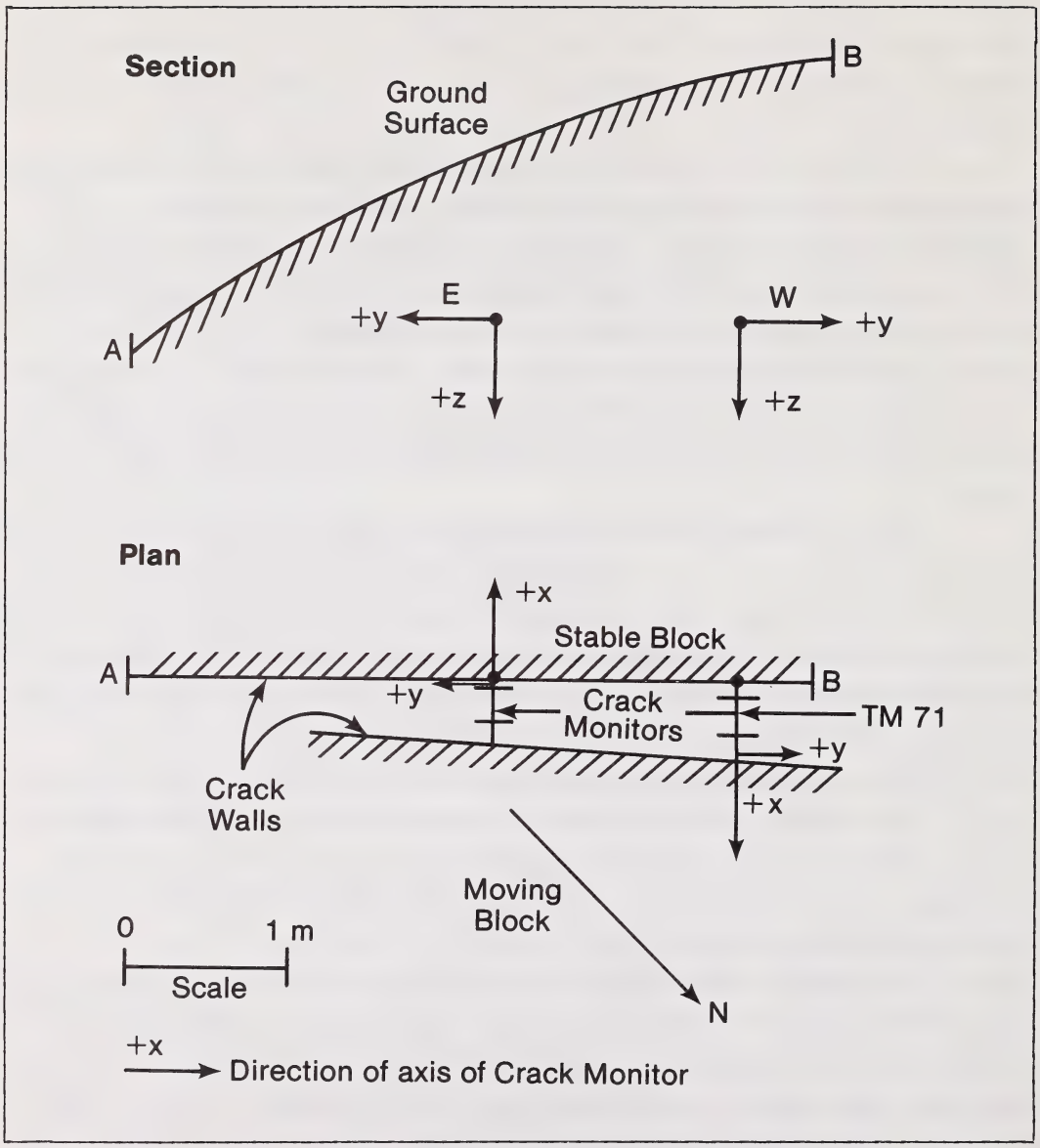


Figure 9. Location of TM 71 crack monitors.

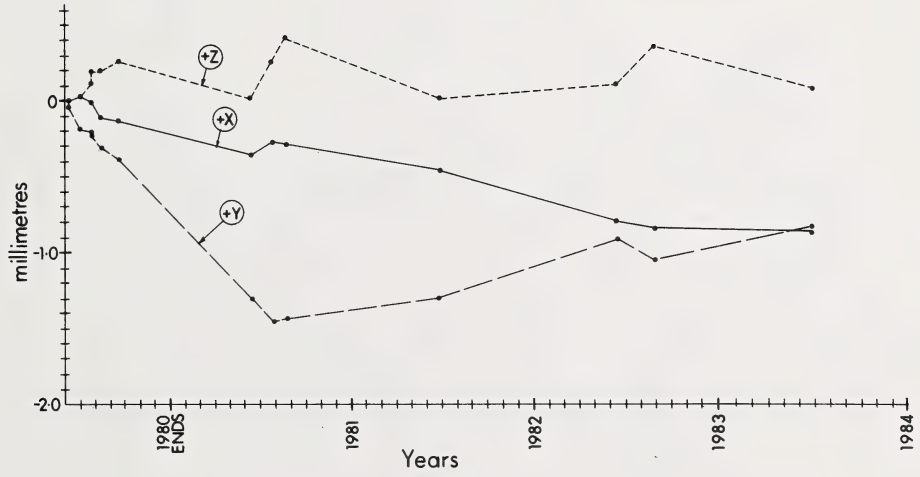


Figure 10. Displacements measured by the eastern TM 71 unit.

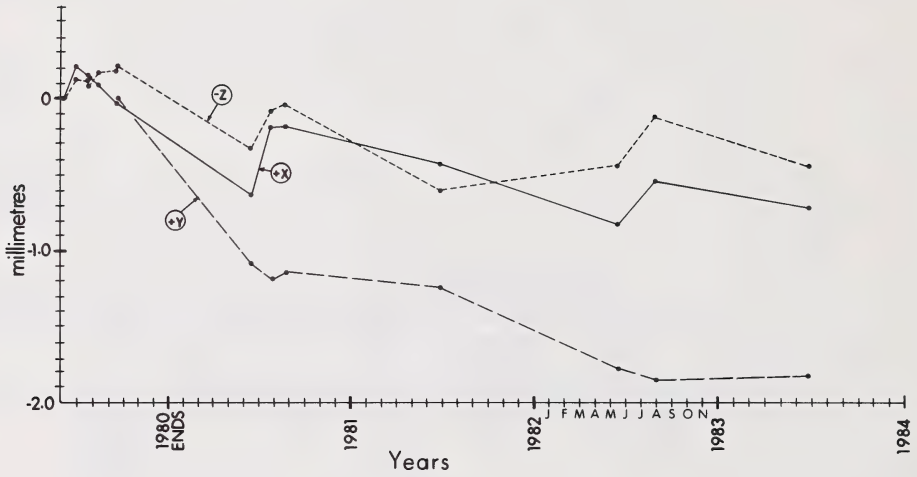


Figure 11. Displacements measured by the western TM 71 unit.

Movements recorded in the z direction are nearly an order of magnitude smaller than the movements in the y direction. The z direction movements agree in sense and show a small downward rotation of the west end of the crack. Movements are seasonal, the mass rising about 0.3 mm over the summer, probably due to thermal expansion.

The x direction movements, normal to the crack, agree in magnitude and sense. There is also good agreement between movements indicated by the horizontal and vertical gauges of both instruments. Movement on the gauges indicate crack closure over the winters of 1980 and 1981; crack opening occurred on both gauges in the summer of 1981.

On 1981 July 18, the gauges were read at hourly intervals for five hours following the initial readings recorded in Tables 3 to 6. Observations form Tables 5 to 8 in Cruden (1983a). Temperature readings from the thermometers attached to the instruments were supplemented by readings from thermistors taped to the rock surface on the north side of the crack below the anchors fastening the instruments to the rock. Temperatures of the instruments ranged over $13^{o}C$ over the five hours. The instruments were in direct sunlight around midday and shaded by the crack later in the afternoon. Values of a and N (Table 3) changed little over the five hours. Thermal corrections of the x measurements based on the instrument temperatures did not result in any significant reduction in the range of displacements in x, which remained at values of about 0.2 mm, comparable to the annual displacements in the x direction recorded in Tables 3 to 6. Similar ranges were recorded for displacements in the y and z directions. The west instrument showed significantly less variation in all three directions than did the east instrument.

The movement recorded by the TM 71 crack monitors is largely a horizontal shear sub-parallel to the wall of Crack 1. One feature of the displacements deserves comment: that is the difference in value of x and y displacement on the two instruments.

One possible explanation of the differences in movements lies in site differences. Figure 9 shows that the eastern instrument is closer to the ground surface and, as the data of Tables 5 to 8 (Cruden 1983a) show, more subject to fluctuations in near-surface atmospheric conditions.

Close to the ground surface, heavy dews typical of the east side of the mountain after warm days saturate the rock. Drying out of the rock mass could cause the contractions in the x direction that have been observed over the summer. Hudec and Sitar (1975) have demonstrated the substantial sensitivity of some Lower Palaeozoic carbonates to moisture; the Mississippian carbonates on Turtle Mountain may show a similar sensitivity. Crack closure over the winter may be due to an increase in moisture content or to ice forming in cracks sub-parallel to Crack 1.

The relatively large seasonal component in the x direction at the deeper west side suggests that rock mass movement in this direction is not as important as mass movement in the y direction. Summer seasonal movements in the x direction, closing Crack 1, may tend to stabilize the rock mass. There are no seasonally stabilizing movements in the y direction. Thus, the greatest rates of horizontal shear movement can be expected in the spring.

3.3 TRILATERAL SIGNS

Eyebolts were installed in the rock to form trilateral signs (Ter Stepanian 1980), and the distances between the bolts measured with a commercial tape extensometer (Slope Indicator Model 518115).

Routine uses of the tape extensometer (for instance, in measuring convergence in tunnels or shafts) employ screw eyes installed so that the axis of the threaded portion of the eye is parallel to the axis of the extensometer. The placement of the screws in this way would have required their installation on the walls of the crack itself, where they would have been subject to the spalling that occurs from the crack walls and the rain of debris into the crack.

These difficulties were avoided by driving the eyes into the surface of what appeared to be hard rock locally free of fractures and some metres distant from Crack 1. Anchors for the bolts can be hammered 3 cm or so into the rock with a hand driver in about 20 minutes. The screw eye and anchor can then be grouted with an epoxy cement and are ready for use when the cement hardens.

The choice of sites for the eyebolts was limited to those where sound, hard rock was exposed at the surface, and to where that surface was

flat or concave so that the tape would not touch it between the anchors. The screw eyes protrude only 3 cm above the rock surface. With these restrictions, nine suitable sites were found, six of which were contiguous and stretched westward from close to Station 2. A map of the signs forms **Figure 12.** Two screw eyes have been damaged by debris sliding down the rock surfaces into which the eyes were driven. D3 was destroyed by a slide of a few cubic metres of rock apparently triggered by a lightning strike between 80/06/11 and 80/07/05 (letter from D. Prosser, Alberta Environment, Edmonton dated July 1980), and was replaced by the eye indicated on Figure 12. E1 was damaged sometime between 83/08/30 and 84/06/26, and the impact by debris appears to have bent the screw eye away from E2.

Observations of the trilateral signs showed random movements of the order of a few millimetres. These movements are within the measurement error of the signs and cannot be regarded as significant.

The three eyebolts in the rock constitute what Ter Stepanian (1980) has described as a simple trilateral sign. These signs may be analysed graphically assuming that the distances A1-A2, A2-A3, and A1-A3 are initially known, and A3-A2 is fixed and unaffected by the movement v in the plane A1-A2-A3 displacing A1 (**Figure 13**).

The analysis proceeds by plotting A1 in its initial position and drawing though it lines parallel to A1-A3 and A2-A1. At some later time, the lengths A1-A3 and A2-A1 will have increased (or decreased) by a3 and a2. Thus, A1 will have moved to A1'. A1' can be located by laying off the distances a3 and a2 along the axes +A3-A3 and +A2-A2 and dropping perpendiculars from a3 and a2 to intersect at A1' (**Figure 14**). The analysis assumes A1-A1' = A3-a3 and A2-A1' = A2-a2. This approximation is good when the angles $\tan^{-1}$ (a3/A2-a2) and $\tan^{-1}$ (a2/A3-a3) are small.

If there is an error, x, in measuring the lengths A1-A3 and A3-A2, then the axes of the error ellipse lie along the bisector of the angle A3 A1 A2 (=θ) and perpendicular to it, and have lengths x sec $\theta/2$ and x cosec $\theta/2$. So when θ is close to 0 or 180 degrees, large apparent displacements of A1 may occur as a result of small errors in measuring A1-A3 and A3-A2.

Data in Cruden (1982b, Table 2) suggested that x may be of the order or 2.5 mm (0.1 in.) over a summer, or 10 times the short-term accuracy of the

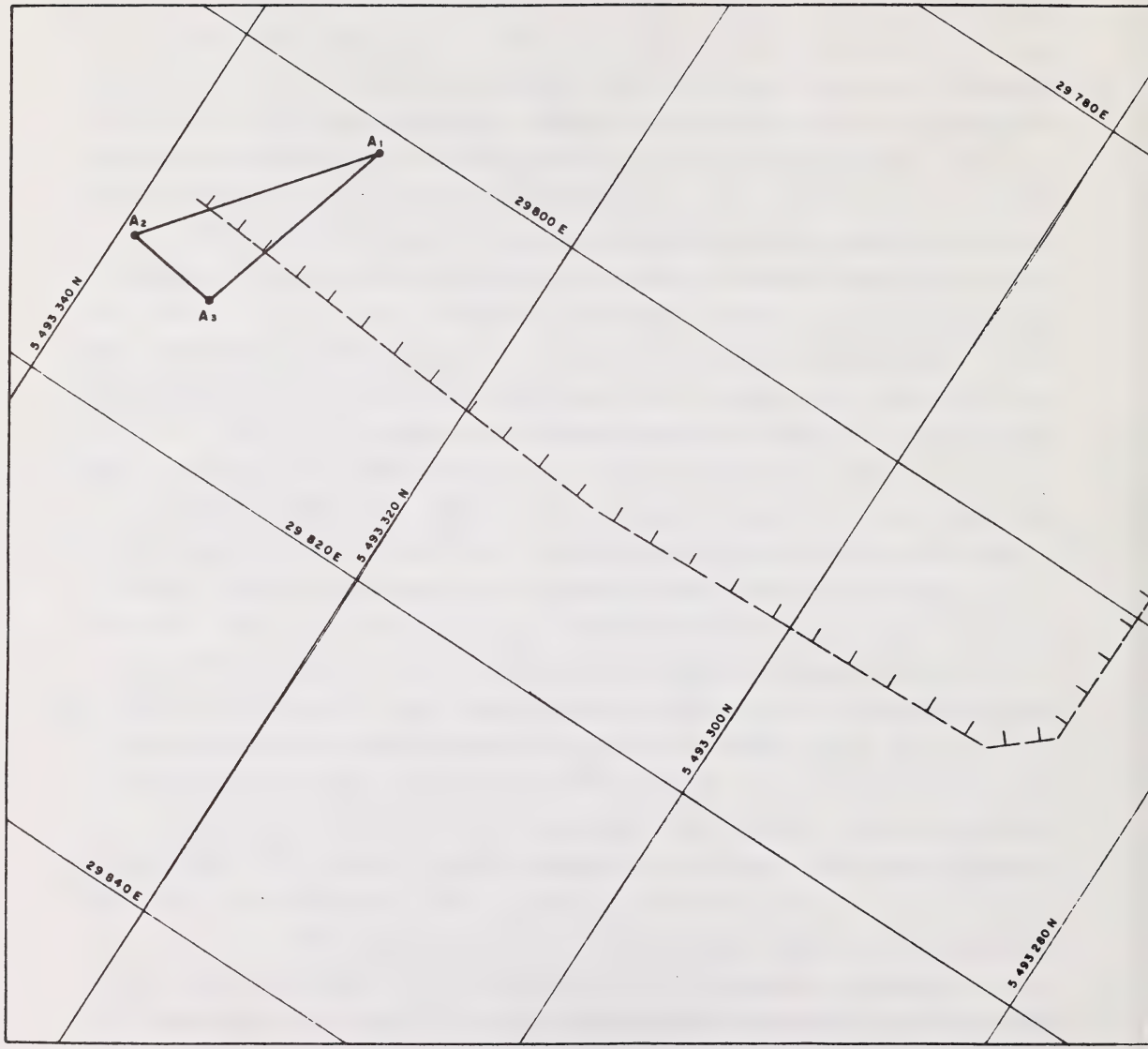
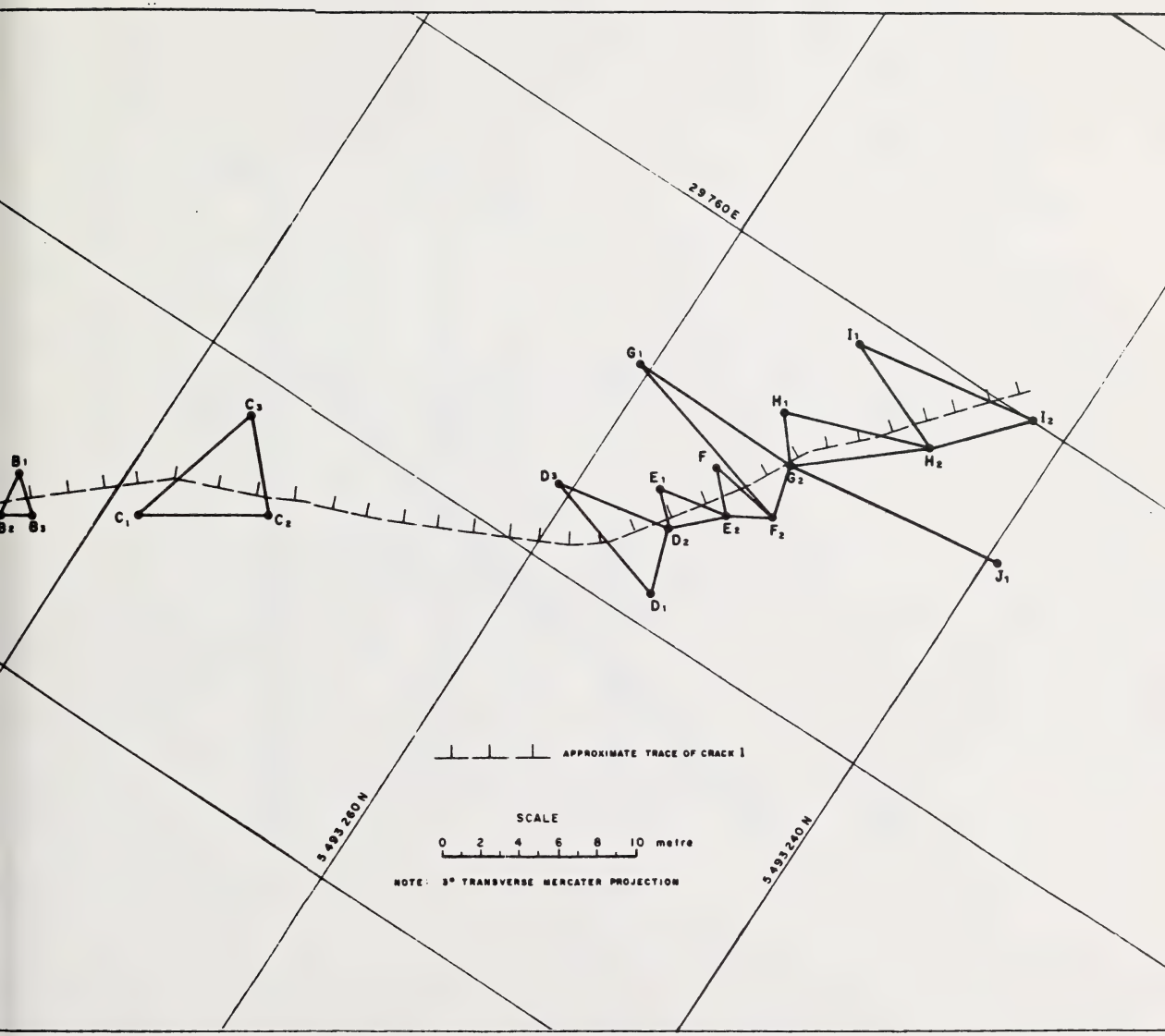


Figure 12. Map of the trilateral signs.


29760E
5493260N
5493240N
B1
B2
B3
C1
C2
C3
D1
D2
D3
E1
E2
F
F2
G1
G2
H1
H2
I1
I2
J1
APPROXIMATE TRACE OF CRACK 1
SCALE
0 2 4 6 8 10 metre
NOTE: 3° TRANSVERSE MERCATER PROJECTION

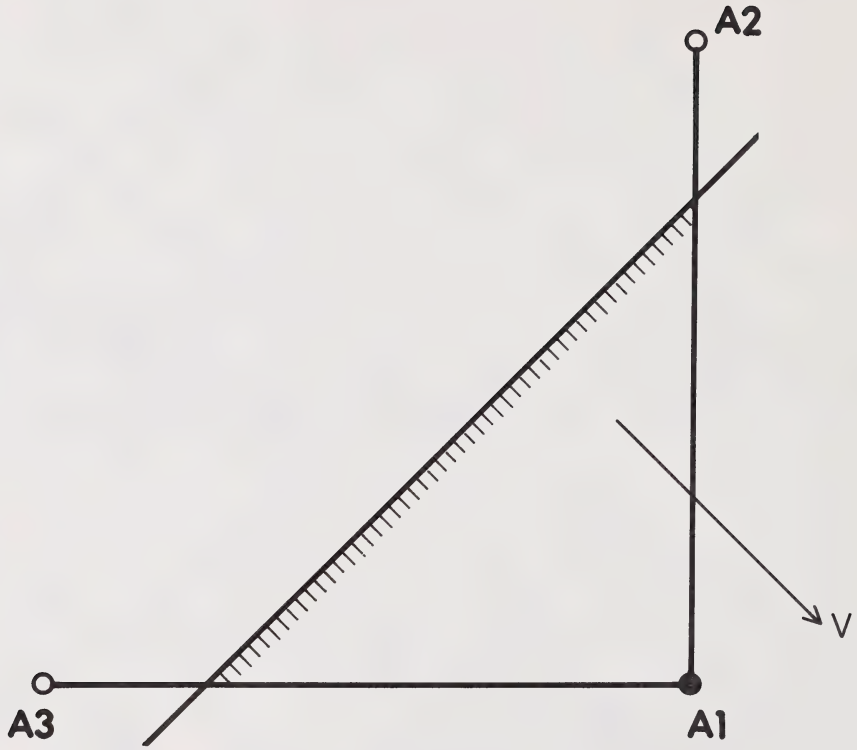


Figure 13. A trilateral sign. The eyebolt at A1 has been displaced in the direction of the arrow by an amount, v, along the crack indicated. A2 and A3 have not moved.

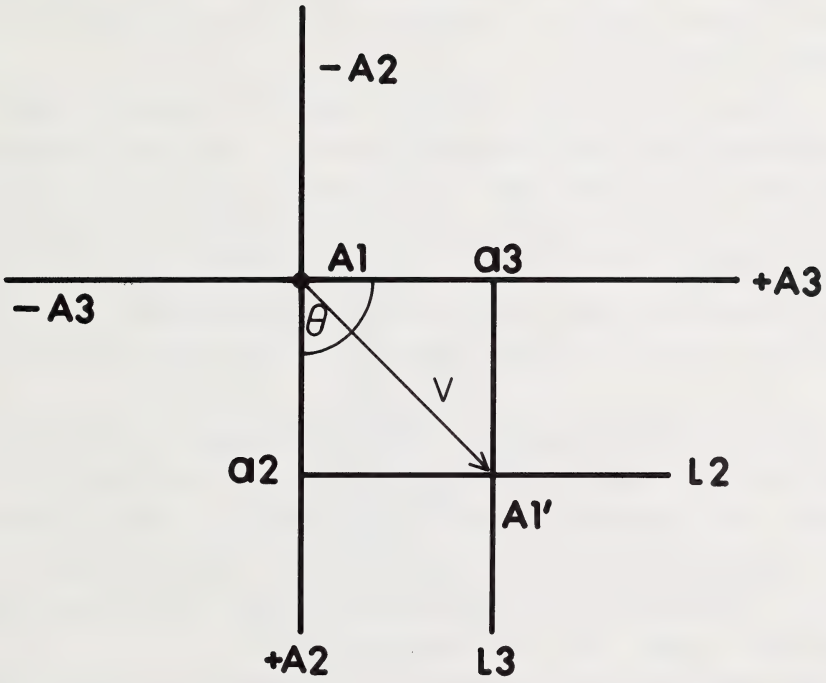


Figure 14. Analysis of trilateral sign data from Figure 13. A1' is the new position of A1 caused by changes a2 and a3 in the lengths A2-A1 and A3-A1.

instrument. Adverse site conditions, high winds, and fouling of the tape or the instrument on the rock surface are believed to contribute to this loss of precision. The major axes of the error ellipses have been drawn on plots of the apparent displacements of the trilateral signs that form **Figures 15 to 23.** These figures show that displacements generally lie within the error ellipses. Values of significant displacements form Table 2. Data used to construct the figures are given in Appendix 7.2; software to plot the figures is documented in Appendix 7.3.

To assess the reaction of the rock mass to temperature changes, a second extensometer was installed within a metre of the first extensometer stretched across Sign I (and Crack I). Distance was measured at hourly intervals during a warm July day. The extensometers were slackened off but not dismounted between the six hourly readings. Their temperatures were measured by thermistors taped in contact with the extensometers. Additional thermistors were taped to the rock outcrop and to the rock wall within the crack.

Changes in the two extensometers can be compared directly by converting the length changes into engineering strains and plotting microstrains. Both experiments show the same trend with rising temperature, which is an apparent contraction of the distance between the anchors **(Figure 24).** The maximum difference between readings at the same time is 20 microstrains or about 10% of the recorded strains.

When the strains to be expected from the expansion of the steel tapes are removed, the agreement between the two sets of readings is again good. Temperatures read from thermistors taped to the extensometers were used. The expansion coefficient of the tapes given by the manufacturer (0.000012 per degree Celsius) was used to make corrections. Four of the five sets of readings now agree to within five microstrains.

Despite the removal of the temperature effects on the tape, the range of strains is not significantly reduced. It is worth noting that the temperature recorded by the thermistor taped to the rock surface reached a higher and later peak than temperatures recorded on the extensometers. The extensometers, perched above ground level, are more exposed to the constant cooling breeze on the west face of the mountain than is the rock surface.

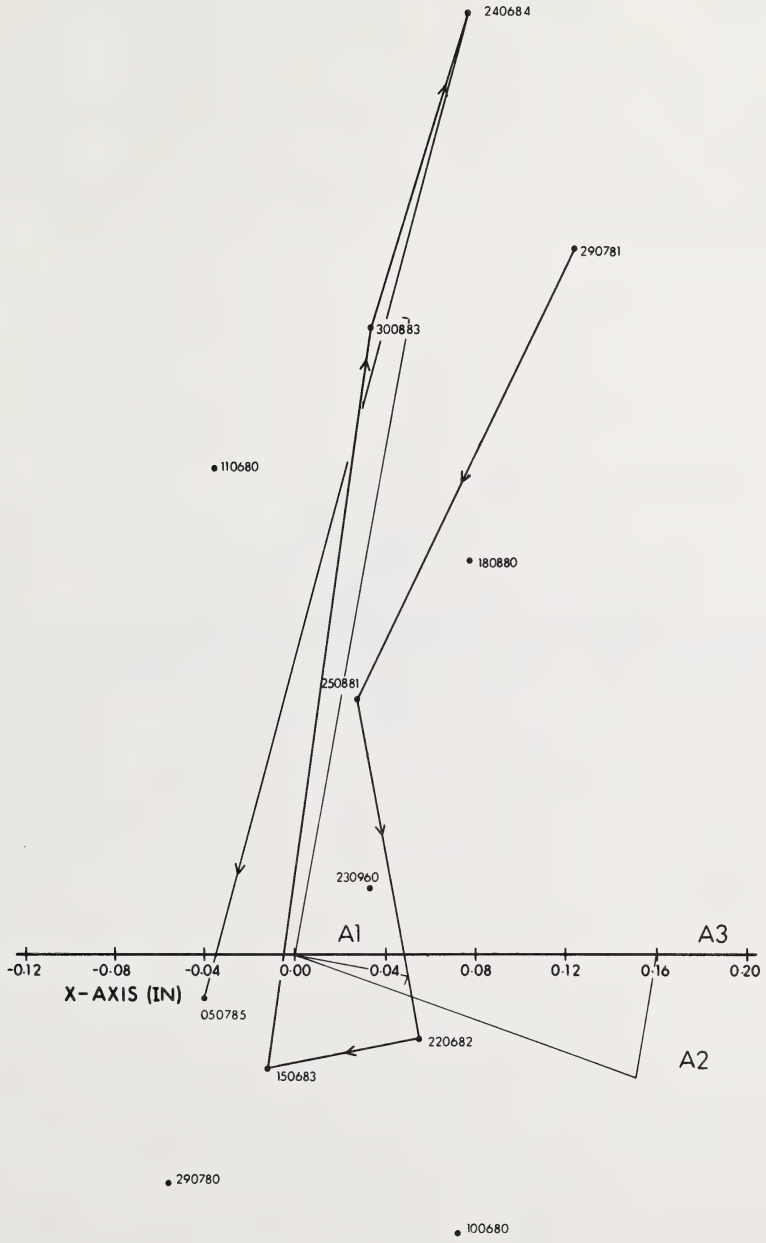


Figure 15. Displacements in Sign A.

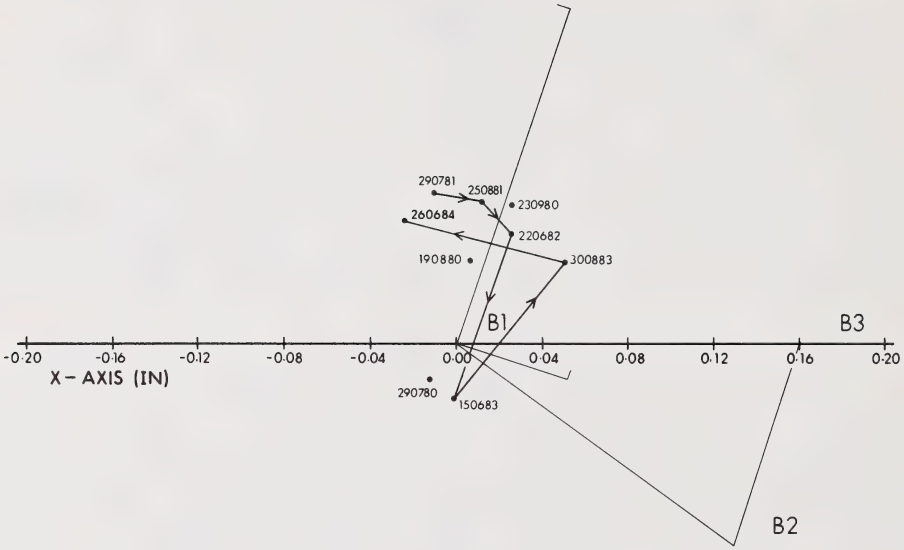


Figure 16. Displacements in Sign B.

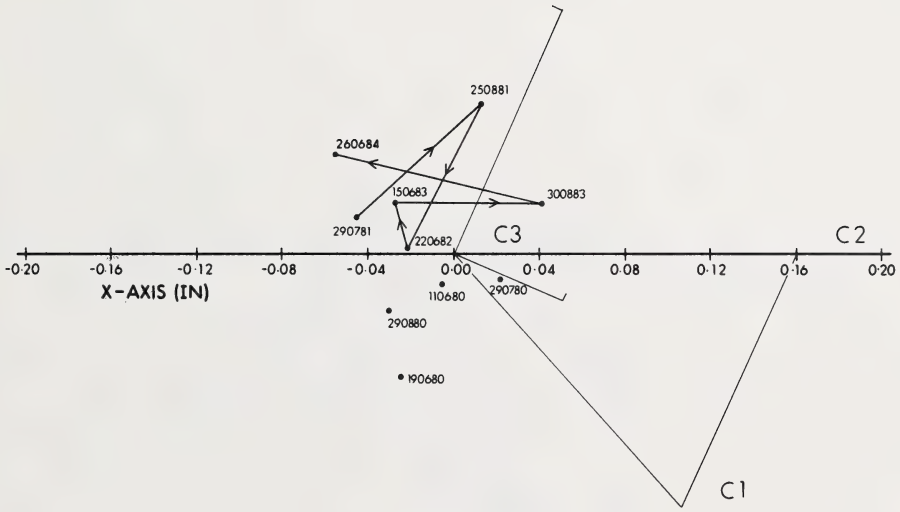


Figure 17. Displacements in Sign C.

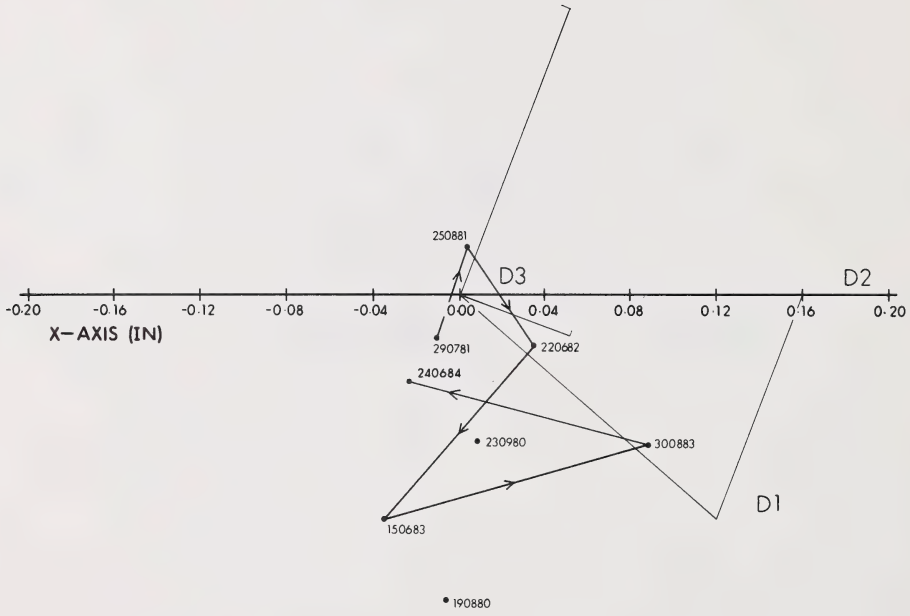


Figure 18. Displacements in Sign D.

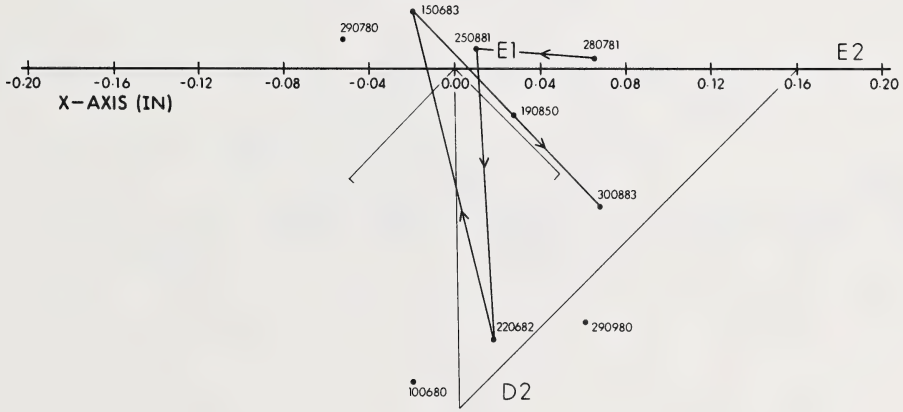


Figure 19. Displacements in Sign E.

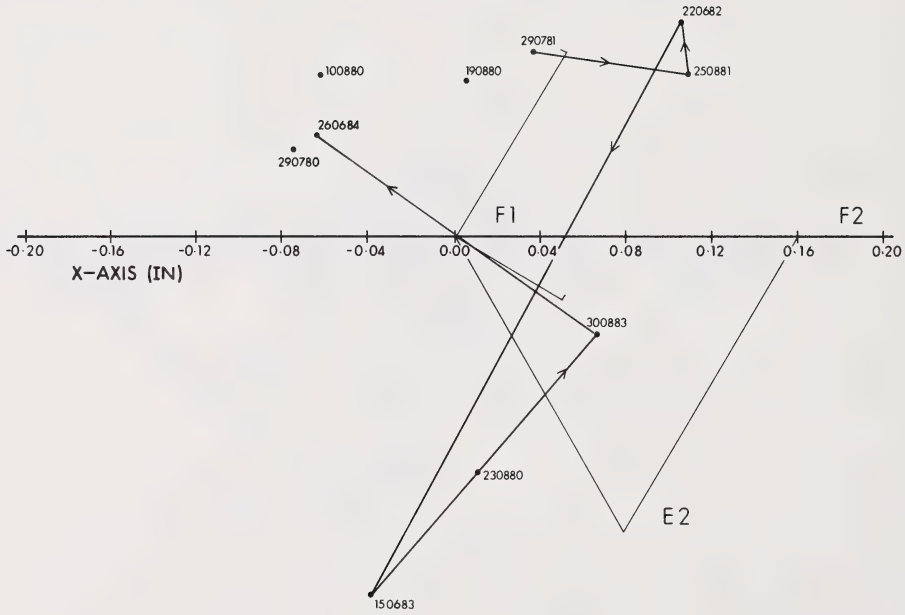


Figure 20. Displacements in Sign F.

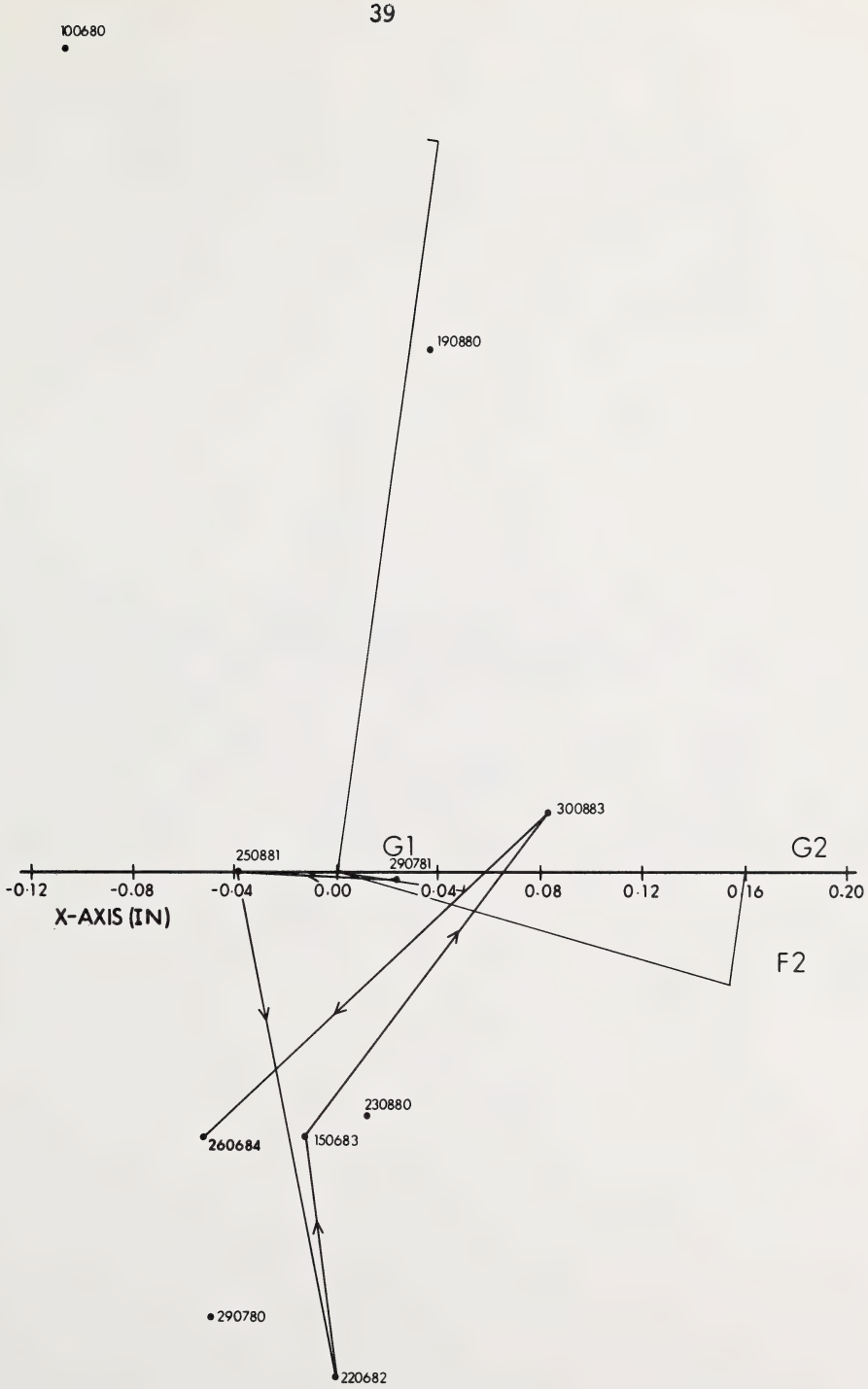


Figure 21. Displacements in Sign G.

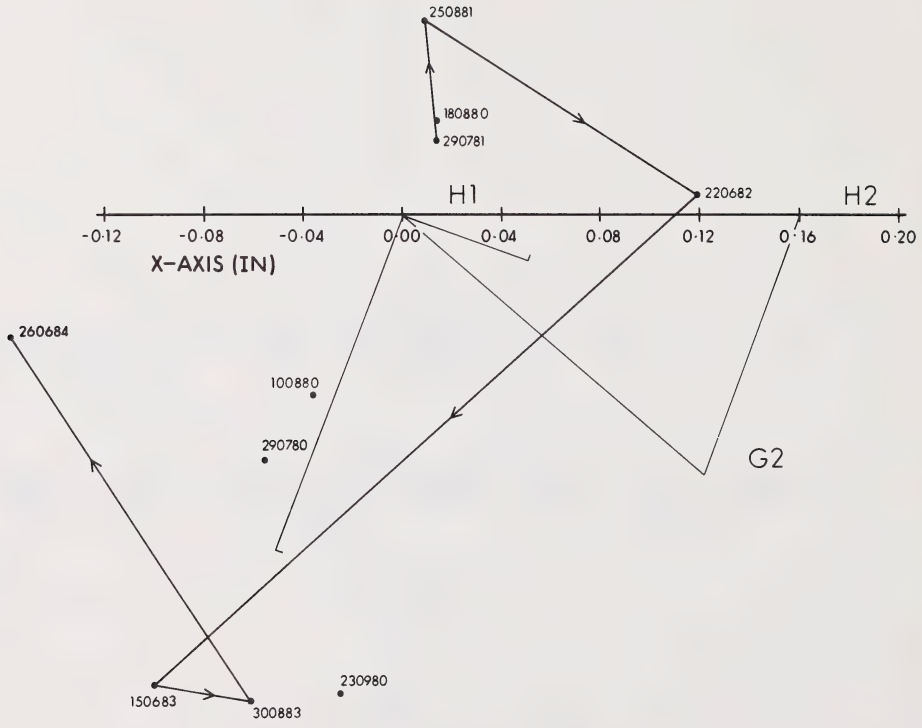


Figure 22. Displacements in Sign H.

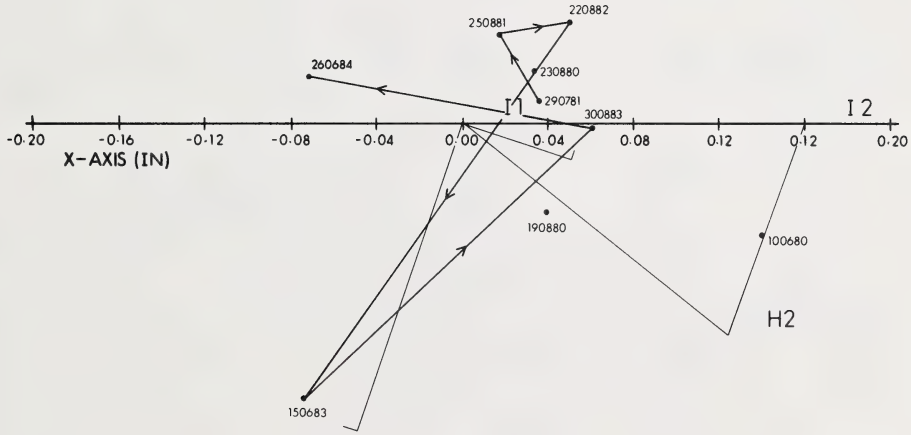


Figure 23. Displacements in Sign I.

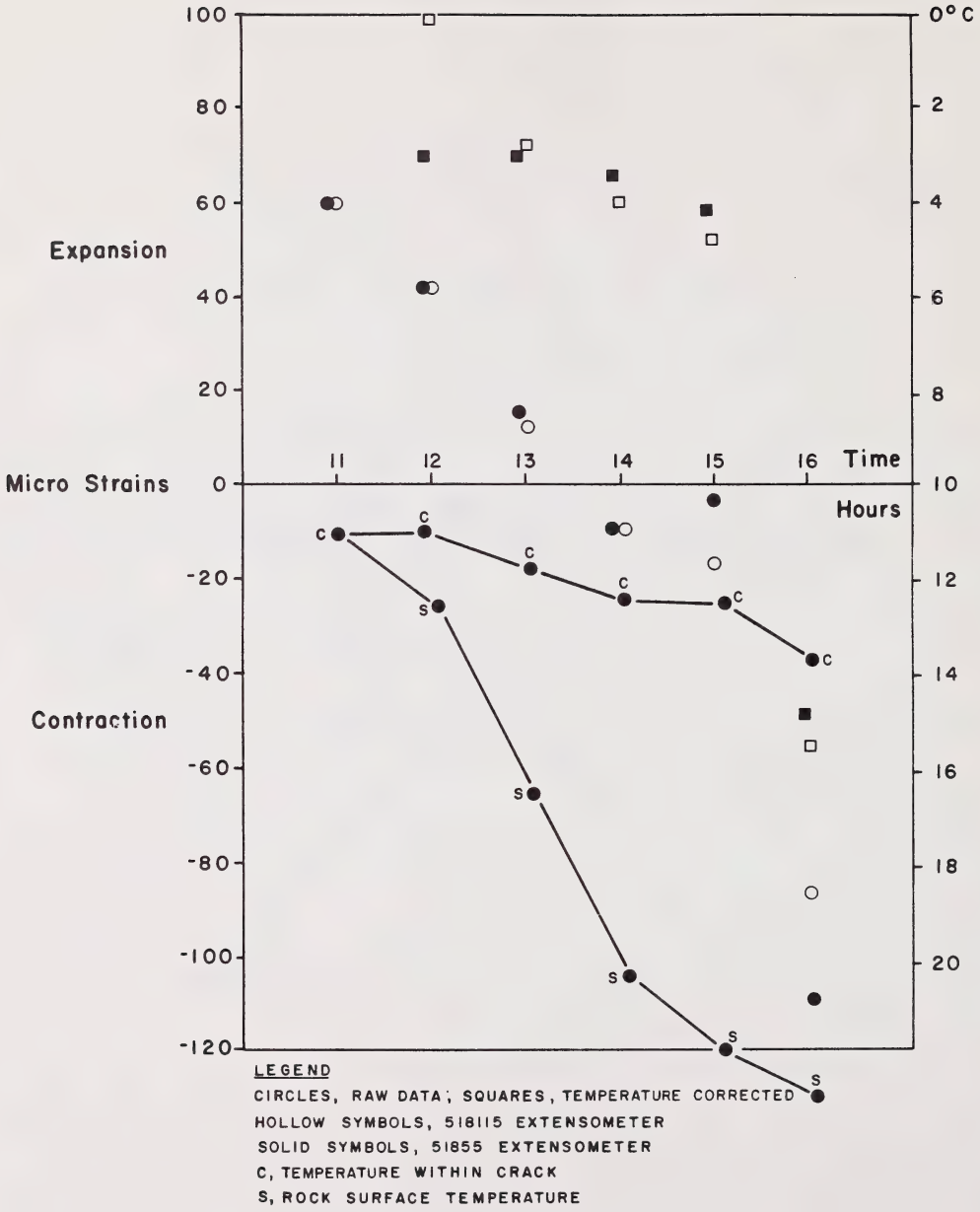


Figure 24. Results of hourly monitoring by tape extensometer.

Table 2. Significant displacements of trilateral signs.

Sign	Theta in Degrees	Significant Displacements	
		Normal (mm)	Shear (mm)
A	16	2.57	14.63
B	36	2.67	8.23
C	48	2.77	6.24
D	41	2.72	7.26
E	89	3.56	3.63
F	60	2.93	5.08
G	16	2.57	14.63
H	41	2.72	7.26
I	39	2.69	7.62

Winkler (1975, Table 12) suggested that the thermal coefficient of limestone lies in the range of 1.7 to 6.8 microstrains per degree Celsius. Taking the rock surface temperature range to be 11.7°C, the maximum thermal expansion thus predicted is 80 microstrains. Temperature range in the crack is considerably less than the range at the ground surface, though it shows a large increase from 1500 to 1500, which is contemporaneous with the large decrease in length shown by both tape extensometers. Supposing then that the movements between the anchors are only due to thermal effects on the rock mass, the displacement is due to rock blocks of considerably greater size than the 6 m or so of gauge length between the anchors.

The displacements recorded by the tapes are an order of magnitude greater than those recorded by the TM 71 units over the same period. The differences may well be caused by the more broken rock on the east face of the mountain at the TM 71 sites and the more sheltered location of the tapes.

Correction of the trilateral signs for rock mass expansion thus requires the calculation of a coefficient of thermal expansion for the rock mass along both the active sides of each trilateral sign. The data in Appendix 7.2 allowed regression of the temperature at which each length was measured against the difference in length. Only one of the 18 regressions shows a correlation coefficient significantly different from random at the 5% level. Clearly, factors other than the air temperature at the time of measurement are influencing the measurements. These factors await discovery and analysis.

3.4 OTHER DISPLACEMENT RECORDS

There is a consensus in rock mechanics literature that "slopes seldome fail without giving ample warning that they are about to do so" (Hoek and Bray 1977:323). Cracks open in the crown of the potential slide and movement rates accelerate to failure. The acceleration is not generally smooth, but may be correlated with rainfalls or thaws, which increase pore pressures in the moving mass. Conversely, dry weather or freezing may slow or terminate displacement.

When the geometry of the moving mass has been defined, monitoring moves to Level III (Larocque 1977) if the mass is not to be stabilized.

Objectives in Level III are to plan measures to minimize disruption resulting from slope failure, and to set a warning level at which these measures come into effect. The level must be sufficiently high to minimize false alarms, yet sufficiently low to give ample warning of impending failure. What constitutes ample warning can only emerge from detailed contingency planning, but a few days should be sufficient.

In what follows, the literature has been briefly reviewed to establish an order of magnitude for a warning level. This review is intended to provide guidance in the design of a remote monitoring system.

Zavodni and Broadbent (1980) have reviewed the displacement records of 13 slides in open pit mines ranging in mass from 0.12×10^6 t to 30×10^6 t. Among their conclusions were:

- It is unlikely that total failure collapse will take place within 24 hours if the displacement velocity is below 17 mm/d (0.055 ft./d.) or within 48 hours if it is below 15 mm/d (0.050 ft./d.).
- A displacement rate above 50 mm/d (0.17 ft./d.) indicates that a failure is probably in the progressive stage and that total collapse could occur with 0 to 48 days.

Calder and Blackwell (1980) report the monitoring of a slide along a gouge zone in a granodiorite at the Brenda Mine, Peachland, British Columbia. After meeting with union and B.C. Mines Department officials, mining proceeded on the understanding that movements of 12 mm/d (0.5 in./d. or 0.24 in./shift) would stop operations in the failure area. During spring thaw, March 1979, movements of 25 mm/d (1 in./d.) halted pit operations, but did not lead to failure.

Brawner et al. (1975) described the monitoring of a failure in the highwall of Hogarth Pit, Steep Rock Mine, Atikokan, Ontario. Among the monitoring devices used were limit switches on wire extensometers, which would trigger alarms if movements of more than 12.5 mm/d (0.5 in./d.) were recorded. These limits were exceeded when temperature drops of $30^{\circ}C$ occurred in a few hours in January, and the limit was increased to 25 mm (1 in.) Failure occurred the following June, and was preceded by movement rates of as much as 300 mm/d (12 in./d.).

MacRae (1982) and Johnson (1982) discussed the monitoring of a one million cubic metre slope movement in the highwall of a working surface coal mine in the Alberta Rockies. Evacuation of the pit began when movements reached 30 mm/h (1.2 in./d.). Slope movement rates peaked in eight hours only, four hours after the pit was evacuated.

The foregoing case histories show that 12 mm/d is the minimum rate considered to indicate a major slope movement is imminent. Experience at Alberta coal mines suggests this rate is conservative. In view of the lack of experience with slope movements in limestone, this rate should be adopted as a warning level, and such rates of movement at Turtle Mountain should be regarded as hazardous.

4. CONCLUSIONS

1. The natural processes that contributed to the Frank Slide are still active and may cause further slope movements. Coal mining has stopped, but it is possible that a fire in the drift mine at Frank is still burning.
2. The monitoring stations set up by Allan do not now adequately cover the margins of the rock wedge whose movement he forecast. They can detect slope movements of about 30 mm normal to the crack margins, but are insensitive to shear movements parallel to the crack margins.
3. TM 71 crack monitors record seasonal displacements of 0.4 mm normal to the crack walls superimposed on noncyclic movements of about 1 mm/a eastward shear. These movements are significant, but not hazardous.

   It is not clear whether the movements are local or represent displacements of the whole of the South Peak rock wedge. The movements may show the terminating effects of displacements caused by the slide and subsequent coal mining, or they may be precursors of the accelerating creep stage of a major slope movement or simply the cumulation of small displacements of loosened surface rock usually known as slope creep.
4. Trilateral signs formed by anchoring eyebolts on either side of gaping cracks can detect movements of about 3 mm normal to the cracks. They are less sensitive to shear movements in their present configuration. No significant movements have been detected in the period from the summer of 1980 to the summer of 1984. The trilateral signs would not have detected the significant movements shown by the TM 71 crack monitors. These movements, induced by diurnal thermal expansion of the rock mass, have been detected by tape extensometers stretched between the eyebolts.

5. Case histories suggest that there would be at least a day before any large rock slide following movements of over 12 mm/d would occur. Such movements should be treated as indications that a major slope movement is imminent, and should be regarded as hazardous.

5. RECOMMENDATIONS

1. Continue monitoring the TM 71 crack monitors and the trilateral sign network at least once a year until the cause of the movements observed on the crack monitors is definitely established.
2. To investigate the movements, continue the survey of microseismic activity to determine whether the fire in the Frank Mine is still burning.
3. Continue analysis and investigation of the trilateral sign network to upgrade its sensitivity to shear displacements along Crack 1. This activity would be assisted by the installation of continuously reading displacement measurement devices across the crack.

6. REFERENCES

Allan, J.A. 1933. Third report on the stability of Turtle Mountain. Department of Public Works. Edmonton, Alberta. 28 pp.

Bayrock, L.A. and T.H.F. Reimchen. 1976a. Surficial geology of the foothills of Alberta. Alberta Research Council. Edmonton, Alberta. Open File Report 1975-24. 72 maps.

Bayrock, L.A. and T.H.F. Reimchen. 1976b. Terrain analysis, Banff National Park. Western Region, Parks Canada. Calgary, Alberta. 17 maps.

Bayrock, L.A. and T.H.F. Reimchen. 1976c. Terrain analysis, Jasper National Park. Western Region, Parks Canada. Calgary, Alberta. 35 maps.

Bayrock, L.A. and T.H.F. Reimchen. 1980. Surficial geology, Alberta Foothills and Rocky Mountains. Alberta Research Council. Edmonton, Alberta. 6 maps.

Brawner, C., P. Stacey, and R. Stark. 1975. Monitoring of the Hogarth Pit Highwall, Steep Rock Mine, Atikokan, Ontario. Proceedings 10th Canadian Rock Mechanics Symposium. Department of Mining Engineering, Queens' University. Kingston, Ontario; II:103-140.

Brock, R.W. 1910a. Letter to the Deputy Minister of Public Works, Edmonton, Alberta, 26 March. Alberta Provincial Archives. File 13048.

Brock, R.W. 1910b. Turtle Mountain, summary report. Geological Survey of Canada. Ottawa. 29 pp.

Brock, R.W. 1911. Turtle Mountain, Frank, Alberta, summary report. Geological Survey of Canada. Ottawa. 13 pp.

Bruce, I.G. and D.M. Cruden. 1980. Simple rockslides at Jonas Ridge, Alberta, Canada. Proceedings International Symposium on Landslides. Sarita Prakashan, New Delhi. I:185-90.

Buttuls, P. and S. Dembo. 1977. Digital plotting. Computing Services, University of Alberta. Edmonton, Alberta. 144 pp.

Calder, P.N. and G. Blackwell. 1980. Investigation of a complex rock slope displacement at Brenda Mines. Bulletin Canadian Institute of Mining. Number 820:73-82.

Cruden, D.M. 1982a. The Brazeau Lake Slide, Jasper National Park, Alberta. Canadian Journal of Earth Sciences 19:975-81.

Cruden, D.M. 1982b. Monitoring the South Peak of Turtle Mountain. Research Management Division, Alberta Environment. Edmonton, Alberta. RMD Report L-77. 63 pp.

Cruden, D.M. 1983a. Monitoring the South Peak of Turtle Mountain, Phases 2 and 3. Research Management Division, Alberta Environment. Edmonton, Alberta. RMD Report OF-59. 43 pp.

Cruden, D.M. 1983b. Monitoring the South Peak of Turtle Mountain. Phase 3: possible modes of ground movement. Research Management Division, Alberta Environment. Edmonton, Alberta. RMD Report OF-60. 42 pp.

Cruden, D.M. and J. Krahn. 1973. A re-examination of the geology of the Frank Slide. Canadian Geotechnical Journal 10:581-91.

Cruden, D.M., D. Prosser, and D.T. Sneddon. 1982. Monitoring the South Peak of Turtle Mountain. Proceedings 4th Canadian Symposium on Mining Surveying and Deformation Measurements. Canadian Institute of Surveying. Ottawa; pp. 335-349.

Daly, R.A., W.G. Miller, and G.S. Rice. 1912. Report of the Commission appointed to investigate Turtle Mountain, Frank, Alberta. Geological Survey of Canada. Memoir 27. 34 pp.

Dowlen, W.E. 1903. The Turtle Mountain rock slide. Engineering and Mining Journal 77:10-12.

Fossey, K. In prep. The structural geology of part of Turtle Mountain, Alberta. Edmonton, Alberta. M.Sc. thesis, Department of Geology, University of Alberta.

Gardner, J.S. 1980. Frequency, magnitude and spatial distribution of mountain rockfalls and rockslides in the Highwood Pass Area, Alberta, Canada. In D.R. Coates and J.D. Vitek. Thresholds in Geomorphology. Allen and Unwin. London; pp. 267-295.

Hoek, E. and J. Bray. 1977. Rock slope engineering. Institute of Mining and Metallurgy. London. 402 pp.

Hudec, P.P. and N. Sitar. 1975. Effect of water sorption on carbonate rock expansivity. Canadian Geotechnical Journal 12:179-86.

Johnson, R.S. 1982. Slope stability monitoring. Proceedings 4th Canadian Symposium on Mining Surveying and Deformation Measurements. Canadian Institute of Surveying. Ottawa; pp. 363-379.

Kerr, F.E. 1979. Crowsnest and its people. Coleman, Alberta:Crowsnest Historical Society. 914 pp.

Kostak, B. 1969. A new device for in situ movement detection and measurement. Experimental Mechanics 9:374-79.

Kostak, B. and J. Rybar. 1978. Measurements of the activity of very slow slope movements. Felsmechanik Kolloquium, Karlsruhe, pp. 191-205. Trans Tech Publications, Clausthal.

Larocque, G. 1977. Pit slope manual. Chapter 8. Monitoring. Canada Centre for Mineral and Energy Technology. Report 77-15. Ottawa. 188 pp.

MacRae, A.M.R. 1982. Case histories of deformation measurements in Canadian surface mines. Proceedings 4th Canadian Symposium on Mining Surveying and Deformation Measurements. Canadian Institute of Surveying. Ottawa; pp. 255-278.

McConnell, R.G. and R.W. Brock. 1904. Report on the great landslide at Frank, Alberta. Annual Report for 1903. Department of the Interior. Ottawa. Part 8. 17 pp.

McKay, B.R. 1931. Stability conditions on Turtle Mountain, Crowsnest Pass District, Alberta: preliminary report. Geological Survey of Canada. Ottawa. 12 pp.

Radbruch-Hall, D.H., R.B. Colton, W.E. Davis, I. Lucchitta, B.A. Skipp, and D.J. Varnes. 1982. Landslide overview map of the conterminous United States. United States Geological Survey. Professional Paper 1183. 25 pp.

Ter Stepanian, G. 1980. Measuring displacements of wooded landslides with trilateral signs. Proceedings International Symposium on Landslides. Sarita Prakashan, New Delhi. I:335-61.

Winkler, E.M. 1975. Stone properties, durability in man's environment. New York: Springer-Verlag. 230 pp.

Whitehouse, I.E. and G.A. Griffiths. 1983. Frequency and hazard of large rock avalanches in the central Southern Alps, New Zealand. Geology 11:331-34.

Zavodni, Z.M. and C.D. Broadbent. 1980. Slope failure kinematics. Bulletin Canadian Institute of Mining. Number 816:69-74.

7. APPENDICES

7.1 DISPLACEMENTS MEASURED BY THE TM 71 UNITS

Table 3. Displacements measured in the vertical plane by the eastern TM 71 unit.

T[a]	Time[b]	Date yy/mm/dd	a[c]	N[d]	xv[e]	xt[f]	xv	z[g]
10	1500	80/06/10	310	1	0.01	0.00	0.01	-0.03
10	1030	80/06/11	000	3	0.01	0.00	0.1	0.03
21	1525	80/07/05	380	1	0.03	-0.045	0.075	-0.01
7	1100	80/07/29	050	3	0.07	0.02	0.05	0.07
26	1530	80/07/29	110	3	-0.02	-0.07	0.05	-0.10
15	1030	80/07/30	085	5	0.04	-0.02	0.06	0.16
11	1055	80/08/19	125	5	-0.04	0.00	-0.04	0.16
4	1100	80/09/23	110	7	-0.04	0.02	-0.06	0.23
2	1200	81/06/16	200	9	-0.300	-0.039	-0.339	0
11	1105	81/07/28	160	11	-0.297	-0.005	-0.292	0.216
25	1223	81/07/25	145	15	-0.325	-0.073	-0.252	0.380
8	1140	82/06/22	200	17	-0.567	-0.010	-0.577	0
10	0830	83/06/14	195	27	-0.897	0	-0.897	0.071
24	1216	83/08/30	180	33	-1.046	-0.068	-0.977	0.307
8	0815	84/06/26	200	31	-1.033	-0.010	-1.043	0

[a]T is the temperature at the time of measurement in degrees Celsius.

[b]Time is the time at which observations are made to the nearest minute.

[c]a is the orientation in grads of the axis of symmetry of the Moire fringe pattern.

[d]N is the number of fringes on one side of the symmetry axis.

[e]xv is the x component in millimetres of the displacement vector on the vertical grid of the TM 71

[f]xt is the thermal correction to xv, (10-T) x 406.4 x 0.000 012 mm.

[g]z is the z component of the displacement vector in millimetres.

Table 4. Displacements measured in the horizontal plane by the eastern TM 71 unit.

T[a]	Time[b]	Date yy/mm/dd	a[c]	N[d]	xh[e]	xt[f]	xh-xt	y[g]
10	1500	80/06/10	335	1	0.02	0.00	0.02	-0.03
10	1030	80/06/11	350	3	0.07	0.00	0.07	-0.07
21	1527	80/07/05	280	7	-0.07	-0.045	-0.025	-0.02
7	1100	80/07/29	290	7	-0.04	0.02	-0.02	-0.23
26	1530	80/07/29	260	9	-0.18	-0.07	-0.11	-0.24
15	1030	80/07/30	280	8	-0.08	-0.02	0.06	0.25
11	1045	80/08/19	275	11	-0.14	0.00	-0.14	-0.34
4	1048	80/09/23	280	13	-0.13	0.02	-0.15	-0.41
4	1057	80/09/23	295	55	-0.144	0.02	-0.164	-1.827
2	1200	81/06/16	285	41	-0.32	0.039	-0.359	-1.329
10	1102	81/07/28	290	45	-0.235	0	-0.235	-1.482
22	1240	81/08/25	285	45	-0.350	-0.059	-0.291	-1.459
8	1140	82/06/22	285	41	-0.310	0.010	-0.329	-1.329
10	0830	83/06/14	260	35	-1.686	0	-0.686	-0.884
24	1216	83/08/30	260	39	-1.764	-0.683	-0.696	-1.022
8	0815	84/06/26	255	33	-0.714	0.010	-0.724	-0.836

[a]T is the temperature at the time of measurement in degrees Celsius.

[b]Time is the time at which observations are made to the nearest minute.

[c]a is the orientation in grads of the axis of symmetry of the Moire fringe pattern.

[d]N is the number of fringes on one side of the symmetry axis.

[e]xh is the x component in millimetres of the displacement vector on the horizontal grid of the TM 71.

[f]xt is the thermal correction to xh, (10-T) x 406.4 x 0.000 012 mm.

[g]y is the y component of the displacement vector in millimetres.

Table 5. Displacements measured in the vertical plane by the western TM 71 unit.

T[a]	Time[b]	Date yy/mm/dd	a[c]	N[d]	xv[e]	xt[f]	xv-xt	z[g]
10	1400	80/06/11	340	3	0.06	0.00	0.06	-0.08
19	1535	80/07/05	350	9	0.21	-0.05	0.2	-0.21
8	1100	80/07/29	355	9	0.23	0.02	0.021	-0.19
26	1530	80/07/29	350	9	0.21	-0.09	0.30	-0.21
15	1030	80/07/30	350	7	0.17	-0.02	0.19	-0.17
23	1430	80/07/30	360	9	0.24	-0.07	0.31	-0.18
12	1110	80/08/19	330	9	0.14	-0.02	0.16	-0.27
5	1140	80/09/23	315	8	0.06	0.04	0.02	-0.26
6	1240	80/09/23	310	9	0.05	0.02	0.03	-0.30
2	1200	81/06/16	175	19	-0.585	0.049	-0.634	2.242
14	1143	81/07/28	200	6	-0.200	-0.024	-0.176	0
20	1352	81/08/25	210	7	-0.230	-0.169	-0.161	-0.037
8	1200	82/06/22	165	15	-0.426	0.012	-0.438	-1.522
10	0910	83/06/14	175	29	-1.893	0	-0.893	0.371
24	1245	83/08/30	195	19	-0.631	-0.085	-0.546	0.051
8	0815	84/06/26	170	27	-0.802	0.012	-0.814	0.409

[a]T is the temperature at the time of measurement in degrees Celsius.

[b]Time is the time at which observations are made to the nearest minute.

[c]a is the orientation in grads of the axis of symmetry of the Moire fringe pattern.

[d]N is the number of fringes on one side of the symmetry axis.

[e]xv is the x component in mm of the displacement vector on the vertical grid of the TM 71.

[f]xt is the thermal correction to xv, (10-T) x 506.4 x 0.000 012 mm.

[g]z is the z component of the displacement vector in millimetres.

Table 6. Displacements measured in the horizontal plane by the western TM 71 unit.

T[a]	Time[b]	Date yy/mm/dd	a[c]	N[d]	xh[e]	xt[f]	xh-xt	y[g]
6	1235	80/09/23	110	15	-0.078	0.024	-0.102	0.494
2	1200	81/06/16	250	25	-0.589	0.049	-0.638	-0.589
13	1138	81/07/28	280	22	-0.277	-0.018	0.209	-0.697
20	1350	81/08/25	275	21	-0.268	-0.061	-0.207	-0.647
8	1200	82/06/22	265	25	-0.435	0.012	-0.447	-0.853
10	0910	83/06/14	265	45	-0.784	0	-0.784	-1.279
24	1245	83/08/30	272	45	-0.639	-0.085	-0.554	-1.357
8	0815	84/06/26	265	47	-0.819	0.012	-0.831	-1.336

[a]T is the temperature at the time of measurement in degrees Celsius.

[b]Time is the time at which observations are made to the nearest minute.

[c]a is the orientation in grads of the axis of symmetry of the Moire fringe pattern.

[d]N is the number of fringes on one side of the symmetry axis.

[e]xh is the x component in millimetres of the displacement vector on the horizontal grid of the TM 71.

[f]xt is the thermal correction to xh, (10-T) x 506.4 x 0.000 012 mm.

[g]y is the y component of the displacement vector in millimetres.

7.2 DATA FROM TRILATERAL SIGNS

The data in Tables 7 and 8 are the differences between the lengths measured at a particular date and those measured on 1980 July 30 and tabulated in Cruden (1982a). The units are inches. The temperature is in degrees Celsius. The lengths measured by the tape extensometer were corrected to a reference temperature of $10^{\circ}C$. The symbol ND indicates no data are available.

Table 7. Data from trilateral signs, 1980.

Station	DATE						
	80/06/10	80/06/11	80/07/29	80/07/29	80/08/19	80/08/19	80/09/23
A1-A2	0.11	-0.106	-0.057	0.02	0.008	0.02	0.019
A1-A3	0.72	-0.033	-0.058	0.057	0.119	0.037	0.033
Temp	18.0	12.5	7.0	16.0	5.0	7.7	2.0
B1-B2	ND	ND	-0.05	0.003	-0.022	-0.012	-0.015
B1-B3	ND	ND	-0.013	0.008	-0.003	0.009	0.025
Temp			7.0	17.0	6.1	7.7	1.0
C1-C3	ND	ND	-0.017	0.062	0.085	-0.036	-0.001
C2-C3	ND	ND	-0.022	0.063	-0.023	-0.022	-0.029
Temp			11.0	13.0	5.9	6.9	2.0
D1-D3	ND	ND	ND	-0.011	0.021	0.159	-0.051
Temp				20.0	5.7	6.3	2.0
D2-D3	ND	ND	ND	0.001	-0.044	-0.008	0.009
Temp				19.0	5.5	7.8	2.0
D2-E1	-0.139	ND	-0.04	0.012	0.021	ND	0.114
Temp	17.0		15.0	16.0	5.40		3.0
E1-E2	ND	ND	-0.071	-0.026	0.026	0.033	0.058
Temp			14.0	15.0	5.4	7.03	3.0
F1-E2	-0.059	ND	-0.133	0.009	0.011	-0.003	0.011
Temp	14.5		16.0	16.0	5.2	7.3	2.0
F1-F2	ND	ND	-0.131	-0.007	0.092	-0.022	0.094
Temp			21.0	16.0	5.4	7.0	2.0
G1-F2	ND	ND	0.006	-0.008	ND	-0.02	0.039
Temp			13.0	18.0		6.9	2.0
G1-G2	-0.103	ND	-0.079	-0.025	0.119	0.05	0.012
Temp	22.5		17.0	18.0	6.0	6.8	2.0
H1-G2	-0.019	ND	-0.022	0.021	ND	-0.026	0.104
Temp	23.0		16.0	17.0		6.9	2.0
H1-H2	-0.035	ND	-0.102	-0.009	ND	0.022	0.026
Temp	25.5		16.0	17.0		7.80	2.0
I1-H2	ND	ND	-0.121	-0.006	0.008	0.106	0.01
Temp			16.0	16.0	4.0	7.9	2.0
I1-I2	0.139	ND	-0.178	0.174	0.024	0.055	0.034
Temp	24.5		16.0	17.0	4.8	7.6	3.0

Table 8. Data from trilateral signs, 1981-1984.

Stations	DATE					
	81/07/29	81/08/25	82/06/22	83/06/15	83/08/30	84/06/26
A1-A2	0.01	-0.012	0.063	0.006	-0.061	-0.073
A1-A3	0.126	0.028	0.051	-0.012	-0.036	0.073
Temp	11.0	13.0	12.0	10.0	10.0	10.0
B1-B2	-0.048	-0.029	-0.010	0.014	0.018	-0.052
B1-B3	-0.01	0.011	0.024	-0.001	0.050	0.023
Temp	10.0	14.0	10.0	12.0	10.0	9.5
C1-C3	-0.04	-0.049	-0.016	0.036	0.010	-0.072
C2-C3	-0.042	-0.013	-0.021	0.027	0.041	-0.056
Temp	8.0	13.0	10.0	11.0	10.0	10.0
D1-D3	0.009	-0.011	-0.043	0.043	0.113	0.008
Temp	11.0	14.0	11.0	11.5	10.0	10.0
D2-D3	0.005	-0.001	0.037	-0.033	-0.089	-0.023
Temp	11.0	14.0	12.0	11.5	10.0	10.0
D2-E1	-0.003	-0.009	0.019	-0.027	0.07	-0.115
Temp	11.0	13.0	11.0	11.5	10.0	10.0
E1-E2	0.062	0.009	0.018	-0.020	0.068	0.336
Temp	11.0	13.0	11.0	11.0	10.0	10.0
F1-E2	-0.054	-0.011	-0.029	-0.029	0.126	-0.072
Temp	11.0	15.0	11.0	11.0	10.0	10.0
F1-F2	0.034	0.093	0.093	-0.037	0.067	-0.064
Temp	11.0	15.0	11.0	11.0	10.0	10.8
G1-F2	0.023	-0.037	0.055	0.016	0.073	-0.019
Temp	11.0	13.0	11.0	11.0	10.0	11.0
G1-G2	0.022	-0.039	-0.044	-0.014	0.083	-0.052
Temp	11.0	13.0	11.0	11.0	10.0	11.0
H1-G2	-0.008	-0.033	-0.084	0.047	0.081	-0.087
Temp	11.0	18.0	11.0	10.0	12.0	12.0
H1-H2	0.014	0.010	0.118	-0.102	-0.063	-0.157
Temp	11.0	18.0	11.0	10.0	12.0	14.0
I1-H2	0.021	-0.013	0.009	0.023	0.490	-0.072
Temp	11.0	16.0	11.0	10.0	12.0	14.0
I1-I2	0.035	0.017	0.048	-0.073	0.061	-0.073
Temp	11.0	16.0	11.0	10.0	12.0	14.0

7.3 DOCUMENTATION OF SOFTWARE FOR TRILATERAL SIGNS

7.3.1 Introduction

This appendix explains the use of the computer program coded for calculating and plotting the measured displacements of trilateral signs in a two-dimensional space. The program is written in FORTRAN IV language. The IBM OS/360 FORTRAN G compiler is used. Digital Plotting System (*Plotlib) at the University of Alberta provided the software to produce plots directly on the Calcomp Model 925/1036 digital plotter and the Statos 4211 electrostatic printer/plotter, both of which are hard copy non-interactive devices.

7.3.2 Theory

The program is mainly based on the Simple Trilateral Sign Measurement Method developed by Ter Stepanian (1980). A simple trilateral sign is a triangle where lengths of three sides are measured (Figure 13). In order to increase the precision, measurements are usually made three times, and average values are calculated. The length of one side, A3-A2, is always assumed to be constant. Graphical construction of a simple trilateral sign is described in Section 3.3 of this report.

7.3.3 Preparation of Input Data

Until the program is changed, all input data must be in Imperial units.

7.3.3.1 Station of the trilateral signs (3A4). Station is equivalent to the marks or observational points in each trilateral sign. Since we use the simple trilateral sign method, we would have three stations for each set of trilateral signs. The program is written for the first input station equal to the observational point (point A1 in Figure 13) on the motion massif, and the second (point A2) and the third (point A3) stations on the motionless massif. The input field can be either character or integer or both.

7.3.3.2 Number of measurements (I3). The program can analyse up to 99 sets of measurements taken in every trilateral sign. These include daily to annual measurements.

7.3.3.3 Length of the changeable sides in trilateral arms (2F10.6). The first changeable side corresponds to the distance between points A1 and A2 mentioned above, and the second changeable side corresponds to the distance between points A1 and A3. The values used in the plotting program are arbitrary and normally not greater than 6 in. because of the length of the plotting paper. They are chosen so they can show a clear trilateral sign in the plot.

7.3.3.4 Angle between the two changeable sides (F10.6). Due to the sign convention in the sine function used in calculating the displacements, and the Cartesian co-ordinate system used in the plotting device, the input inclination R (in radians) is equal to:

R = rad(360 - Theta), where Theta is the angle (in degrees) between the two changeable sides A1-A2 and A1-A3 (Figure 14).

7.3.3.5 Displacement lines or incremental length of the changeable sides (2F10.5). This is the change in length of the changeable sides of the trilateral sign. For the sign convention used in the program, the sign of recorded measurements needs to be reversed when input into the program. Imperial units (inches) are used.

7.3.3.6 Time of measurement (F10.2). The date, month, and year when the measurements are obtained can be plotted beside the displaced position of point A1 on the motion massif.

7.3.4 Run Commands

```
RUN *FORTGTEST SCARDS=SOURCEFILE
RUN -LOAD#+*IG+*PLOTLIB 5=DATAFILE 6=OUTPUTFILE 9=-PLOT
PLOT
CONTINUE
RUN *CALCOMPQ PAR=-PLOT PEN=(GRN, RED, BLU) RETURN=CIVE
C
C
C MONITORING THE MOVEMENT OF THE TURTLE MOUNTAIN
C
C *PLOTTING PROGRAM * - PLOTTING THE ANNUAL MEASUREMENTS OBTAINED FROM THE
MONITORING INSTRUMENTS INSTALLED ON THE SOUTH PEAK OF THE TURTLE MOUNTAIN
C
C TO RUN THE PROGRAM, TYPE IN:
C RUN *FORTGTEST SCARDS=SOURCEFILE
C RUN -LOAD#+*IG+*PLOTLIB 5=DATAFILE 6=OUTPUTFILE 9=-PLOT
C PLOT
C CONTINUE
C RUN *CALCOMPQ PAR=-PLOT PEN=(GRN, RED, BLU) RETURN=CIVE
C
C THE COMMAND FOR PEN COLOUR IS OPTIONAL.  IGNORE PEN=( )
C THE DEFAULT PEN COLOUR IS BLACK
C
C TO INPUT THE MEASUREMENTS INTO THE DATAFILE: REVERSE THE SIGN OF
MEASUREMENTS, THAT IS, THE POSITIVE SIGN OF THE MEASURED VALUES SHOULD BE
CHANGED TO NEGATIVE WHEN INPUTTING THEM INTO THE DATAFILE
C
C *ALL INPUT MEASUREMENTS MUST BE IN IMPERIAL UNITS*
C
C
C INPUT THE STATIONS OF THE TRILATERAL SIGNS
C
      READ(5,7)M1,M2,M3
    7 FORMAT(3A4)
      WRITE(6,7)M1,M2,M3
```

```
C
C INPUT THE NUMBER OF YEARS OF READING, LENGTH OF THE TWO ARMS OF THE
TRILATERAL SIGN, AND THE ANGLES (IN RADIANS) BETWEEN THE ARMS
C
      READ(5,10)N,S1,S2,P
   10 FORMAT(I3,3F10.6)
      WRITE(6,10)N,S1,S2,P
      I=0
      D1=0.0
      D2=0.0
      AX=0.0
      AY=0.0
      X1=0.0
      X2=0.0
      Y1=0.0
      Y2=0.0
      Y3=0.0
      DD2=0.0
      YY3=0.0
      DATE=0
C
C CALCULATION OF THE CO-ORDINATES OF THE INCLINED ARM FROM THE HORIZONTAL
C
      AX=S1*COS(P)
      AY=S1*SIN(P)
      WRITE(6,20)AX,AY
   20 FORMAT(2F10.4)
C
C CALL PLOTS SUBROUTINE TO PLOT UP THE TRILATERAL SIGNS
C
      CALL PLOTS
      CALL METRIC(0)
      CALL PLOT(18.0,14.0,-3)
      CALL PLOT(S2,0.0,2)
```

```
                CALL PLOT(AX,AY,2)
                CALL PLOT(0.0,0.0,2)
                AAX=AX+0.1
                AAY=AY+0.1
                SS2=S2+0.1
                CALL SYMBOL(0.1,0.1,0.2,M1,0.0,4)
                CALL SYMBOL(AAX,AAY,0.2,M2,0.0,4)
                CALL SYMBOL(SS2,0.1,0.2,M3,0.0,4)
                PT=6.2832-P
C
C DO LOOP TO INPUT THE ANNUAL MOVEMENTS (IN INCHES) OF THE TRILATERAL SIGNS
AND CALCULATE THEIR POSITION IN TERMS OF THE CARTESIAN CO-ORDINATE SYSTEM
C
                DO 25 I=1,N
                READ(5,30)D1,D2,DATE
             30 FORMAT(2F10.5,F10.2)
                WRITE(6,30)D1,D2,DATE
C
C DETERMINATION OF THE ANGLE USED IN CALCULATING THE DISPLACEMENT OF THE D1
ARM IN CARTESIAN CO-ORDINATES
C
                IF(D1.GE.0.0000)GO TO 35
                GO TO 37
             35 PD=P-3.1416
                GO TO 39
             37 PD=P
C
C CALCULATION OF THE DISPLACEMENTS OF THE TWO ARMS, D1 & D2, IN TERMS OF THE
CARTESIAN CO-ORDINATES
C
             39 Y1=ABS(D1)*SIN(PD)*50*0.5
                X1=ABS(D1)*COS(PD)*50*0.5
                D2=D2*(-50)*0.5
                X2=D2-X1
```

```
                Y2=X2/TAN(PT)
                Y3=Y1+Y2
                WRITE(6,40)X1,X2,Y1,Y2,Y3
             40 FORMAT(5F10.4)
C
C CALL SYMBOL SUBROUTINE TO PLOT THE DISPLACED MONITORED TRILATERAL SIGN "O"
C
                CALL SYMBOL(D2,Y3,0.05,11,0.0,-1)
                DD2=D2+0.1
                YY3=Y3+0.1
C
C CALL NUMBER SUBROUTINE TO PLOT THE POSITION OF THE ANNUAL DISPLACED
TRILATERAL SIGNS IN THE CO-ORDINATE SYSTEM
C
                CALL NUMBER(DD2,YY3,0.05,DATE,0.0,-1)
                WRITE(6,50)D2,Y3,DD2,YY3,DATE
             50 FORMAT(4F10.4,F10.2)
             25 CONTINUE
C
C CALL AXIS2 SUBROUTINE TO PLOT THE X- AND Y-AXIS ON THE CO-ORDINATE SYSTEM
C
                CALL METRIC(0)
                CALL AXIS2(-5.0,0.0,'X)
                AXIS(IN)',-10,10.0,0.0,-0.2000,0.0400,1.0)
C
C TERMINATES THE PLOT SUBROUTINE
C
                CALL PLOT (0.0,0.0,999)
                STOP
                END
```

7.3.5 Ouput from Run Commands (see also worked example)

The output will include:

1. Print-out, which shows the stations that made up the trilateral sign, the number of measurements, the length of the changeable sides used in the plot, the angle (in radians) used in the plot, then the calculated x, y co-ordinates of the displaced observational points (point A1) in each measurement, and the corresponding time when those measurements were taken.
2. Plots of the displaced observational points in every trilateral sign in a Cartesian co-ordinate system.

7.3.6 Worked Example

Included in this example are the displacements measured at the trilateral sign of Station A between 1980 and 1983, the input data, and the resulting print-out. Station A is located at the South Peak of Turtle Mountain, southern Alberta. The computer plot has formed the basis of Figure 15.

INPUT FILE

```
A1, A2, A3
10, 4.0, 4.0, 5.9341
-0.1095, -0.07143, 100680.
0.1048, 0.03333, 110680.
0.0190, 0.05714, 290780.
-0.01429, -0.07857, 190880.
-0.02143, -0.03333, 230980.
-0.01191, -0.12620, 290781.
0.01191, -0.02857, 250881.
-0.06429, -0.05476, 220682.
-0.0060, 0.0120, 150683.
0.0610, -0.0360, 300883.
```

OUTPUT FILE

```
A1 A2 A3
10 4.000000 4.000000 5.934100
3.7587 -1.3682
-0.10950 -0.07143 100680.00
2.5724 -0.7866 -0.9363 -2.1610 -3.0974
1.7858 -3.0974 1.8857 -2.9974 100680.00
0.10480 0.03333 110680.00
-2.4620 1.6287 0.8962 4.4744 5.3706
-0.8332 5.3706 -0.7332 5.4706 110680.00
0.01900 0.05714 290780.00
-0.4463 -0.9821 0.1625 -2.6982 -2.5357
-1.4285 -2.5357 -1.3285 -2.4357 290780.00
-0.01429 -0.07857 190880.00
0.3357 1.6285 -0.1222 4.4739 4.3517
1.9642 4.3517 2.0642 4.4517 190880.00
-0.02143 -0.03333 230980.00
0.5034 0.3298 -0.1832 0.9061 0.7228
0.8332 0.7228 0.9332 0.8228 230980.00
-0.01191 -0.12620 290781.00
0.2798 2.8752 -0.1018 7.8987 7.7969
3.1550 7.7969 3.2550 7.8969 290781.00
0.01191 -0.02857 250881.00
-0.2798 0.9940 0.1018 2.7308 2.8327
0.7142 2.8327 0.8142 2.9327 250881.00
-0.06429 -0.05476 220682.00
1.5103 -0.1413 -0.5497 -0.3882 -0.9379
1.3690 -0.9379 1.4690 -0.8379 220682.00
-0.00600 0.01200 150683.00
0.1410 -0.4410 -0.0513 -1.2114 -1.2627
-0.3000 -1.2627 -0.2000 -1.1627 150683.00
0.06100 -0.03600 300883.00
```

```
-1.4330 2.3330 0.5216 6.4092 6.9309
0.9000 6.9309 1.0000 7.0309 300883.00

F=DMC25.REV
```

N.L.C. - B.N.C.
3 3286 06707329 2